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STATE OF OHIO
MICHAEL V. DISALLE, Governor
DEPARTMENT OF NATURAL RESOURCES
HERBERT B. EAGON, Director
DIVISION OF GEOLOGICAL SURVEY
RALPH J. BERNHAGEN, Chief

REPORT OF INVESTIGATIONS NO. 41

PETROLOGY OF PRECAMBRIAN ROCKS OF OHIO

By

George R. McCormick

COLUMBUS

1961

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PURPOSE AND SCOPE

The purpose of the present study is to give a detailed petrologic description of the Precambrian rocks in some wells in Ohio. The last study of this nature on the Precambrian in Ohio wells was in 1939, at which time only eight wells had been drilled into the basement rocks and only three of these had been studied. Since 1939, twenty-one wells have been drilled into the basement and three of these wells have been partially cored. The location, and certain other information, for the known wells in Ohio that penetrate Precambrian rock are given in table 1 and figure 1. The samples and cores from the twenty-one wells drilled since 1939 were studied in detail by the writer, and interpretations of petrogenic relationships were made. The data compiled by workers on the Precambrian wells drilled before 1939 were reevaluated in light of the studies on wells drilled since that year. Specific gravity determinations were run on some rock types in the well cores to aid in the interpretation of gravity maps of Ohio.

METHODS OF INVESTIGATION

Well Cores

The well cores were studied megascopically and the rock types in them were described. From the various rock types in the cores, thirty-seven selected thin sections were cut and were studied under the polarizing microscope. Percentages of minerals present in each thin section were determined by the use of the Chayes stage and Denominator counter. The compositions of the feldspars were determined by studying the index of refraction and by using the Michel-Levy method with the Leitz universal stage. Minerals of questionable identity in the thin sections and varieties of garnets, were examined in index of refraction oils and identifications were made on the basis of the index or indices of refraction, 2V, or birefringence.

Well Cuttings

The well cuttings were examined first with a binocular microscope. A log was made for each well, listing kinds and approximate amounts of minerals in each sample interval and any information as to rock type which could be derived from lithic fragments and minerals present. These logs then were examined, and sample intervals containing nearly the same content in both kind of rock and percentage of minerals were grouped together. These sample intervals were then divided into sections if they extended over a range greater than 25 feet. From each unit or 25-foot interval, a 25-gram sample of lithic and mineral fragments was crushed and sieved through a 150-mesh screen; the fragments remaining on a 200-mesh screen were retained. Magnetite and drill bit particles were removed from the sieved sample with a hand magnet. The removed particles were put in dilute nitric acid, which dissolved the drill bit particles, leaving the magnetite, which was weighed on a beam balance. The nonmagnetic fragments were separated into light

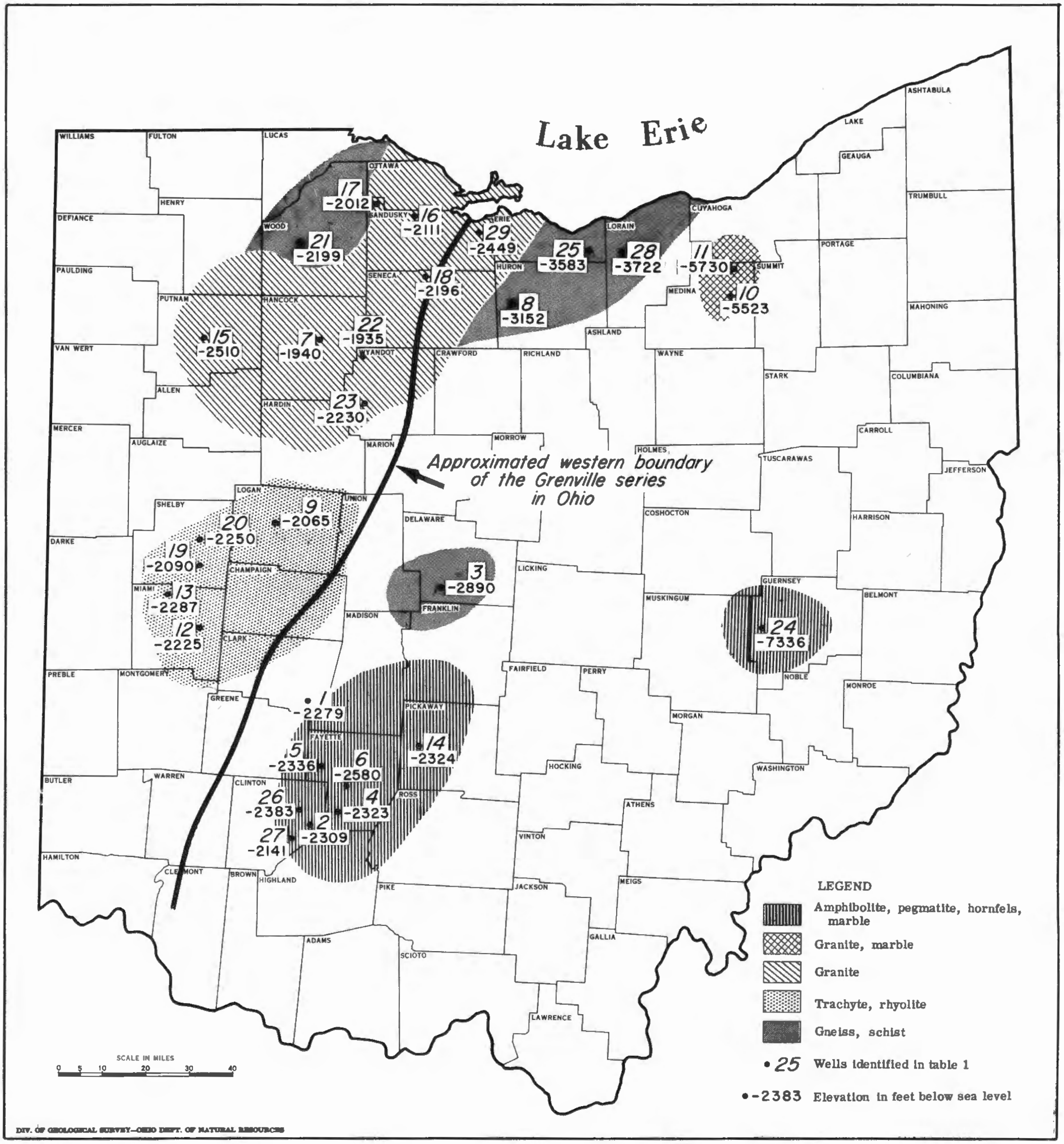

Figure 1. - Location of wells in Ohio that penetrate the Precambrian. Well numbers and the elevation and lithologic type of the top of Precambrian rocks are shown by the appropriate numbers and patterns.

TABLE 1. - GEOGRAPHIC LOCATION AND ELEVATION OF WELLS PENETRATING THE PRECAMBRIAN IN OHIO

County	Township	Well name	Elevation of well head (feet)	Elevation of crystalline rock (feet)	Number in figure 1	Date completed	O. G. S. well sample number[1]
Clark	Madison	Friend	1087	-2279	1	1926	476
Clinton	Wayne	Adams	1081	-2309	2	1958	772
Clinton	Wayne	McVey	1083	-2380	26	1959	837
Clinton	Wayne	Van Pelt	1084	-2126	27	1959	813
Delaware	Orange	Vance	920	-2890	3	1934	402
Erie	Florence	Sayler	817	-3583	25	1960	887
Fayette	Concord	Wilson	1017	-2323	4	1957	751
Fayette	Jasper	Barnes	1044	-2336	5	1958	767
Fayette	Union	Hopkins	965	-2580	6	1957	750
Guernsey	Adams	Marshall	994	-7331	24	1961	925
Hancock	Marion	Norris	830	-1940	7	1912	477
Huron	Peru	Arting	749	-3152	8	1937	163B
Logan	McArthur	Johns	1190	-2065	9	1947	192 (Core 645)
Lorain	Henrietta	Borne	848	-3722	28	1960	894
Medina	Granger	Warner	1116.7	-5523	10	1959	812
Medina	Hinckley	Smith	1200	-5730	11	1959	819
Miami	Lost Creek	Walker	1030	-2225	12	1958	764
Miami	Washington	Levering	995	-2287	13	1955	669
Pickaway	Monroe	Long	856	-2289	14	1959	786
Putnam	Liberty	Barlage	740	-2510	15	1944	156
Sandusky	Rice	Hetrick	590	-2111	16	1936	No samples
Sandusky	Townsend	Haff	641	-2449	29	1960	895
Sandusky	Woodville	Bruns	655	-2012	17	1902	305
Seneca	Pleasant	Watson	704	-2196	18	1912	No samples
Shelby	Perry	Nelson	1049.7	-2090	19	1955	687
Shelby	Salem	Fogt	1037.3	-2250	20	1956	702
Wood	Liberty	Killian	685	-2199	21	1937	626
Wyandot	Crawford	Nora Heck	860	-1935	22	1942	99
Wyandot	Jackson	Parsell	810	-2230	23	1947	171

1. Ohio Division of Geological Survey.

and heavy mineral fractions in bromoform and each fraction was weighed. Percentages of heavy and light minerals for each sample were calculated from these weights together with the weights determined for the magnetite. The separated fractions were mounted in canada balsam and studied under the petrographic microscope. Percentages of minerals present in each slide were estimated visually, and marked increases or decreases of all minerals were noted. Any mineral which could not be identified accurately in balsam was checked in index of refraction oils.

Specific Gravities

To determine the range in specific gravities of the rock types in the cores, random samples were taken from various parts of each rock. The samples were allowed to soak in distilled water for 48 hours before they were weighed, allowing the pores to become saturated so that the specific gravity determined would closely approximate the specific gravity of the sample in the ground. After the specimens soaked 48 hours, their specific gravity was determined on a Jolly spring balance (table 2).

TABLE 2. - SPECIFIC GRAVITIES OF ROCK TYPES FOUND IN WELL CORES

Well name	Depth of sample from surface (feet)	Rock type	Specific gravity
Hopkins	3752	Pyroxene hornfels	3.58
	3755	Pyroxene hornfels	3.42
	3895	Marble	2.81
	3898	Marble	3.10
	4135	Marble	2.81
	4706	Amphibolite	3.17
	4700	Amphibolite	3.15
	4708	Granite pegmatite	2.67
Smith	7030	Granite gneiss	2.65
	7034	Chloritic marble	2.77
	7037	Granitic gneiss	2.59
Johns	3300	Rhyolite	2.61

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. George E. Moore, Jr. of The Ohio State University, who suggested the problem and supervised the petrographic study and the preparation of this report.

Grateful acknowledgment is made to the Ohio Division of Geological Survey for making the problem available and for supplying funds for the preparation of thin sections and procuring of laboratory supplies. Mr. George Shearrow of the Survey supplied information concerning well locations and aided in obtaining well samples and cores.

Invaluable advice concerning some of the thin sections and the taking of photomicrographs was given by Dr. Carl A. Lamey of The Ohio State University. Photomicrographs were taken with the able assistance of Mr. Richard Krushensky and paid for by the Texaco Fund of the Department of Geology.

The writer acknowledges Dr. Ernest Ehlers of the Department of Mineralogy of The Ohio State University for his advice in the determination of various minerals, to Dr. H. J. Pincus of the Department of Geology of The Ohio State University for his advice in the determination of wet densities, and to Dr. Manuel N. Bass of the Carnegie Institute for information regarding the ages of the Precambrian rocks of Ohio that were studied.

LITERATURE ON PREVIOUS WORK

The first well to penetrate the Precambrian in Ohio was drilled near Findlay in 1912, and the Precambrian rock in this well was described by Condit (1913) as granite gneiss.

T. D. Friend of Columbus, in 1926, drilled a well near South Charleston into the Precambrian. Because this well was located not far from the axis of the Cincinnati arch, it was expected that the well would penetrate granite gneiss like that in the well near Findlay. However, the well penetrated 800 feet of black carbonaceous limestone, and no granite gneiss, beneath the basal Cambrian arkose (Wasson, 1932).

The Bruns well penetrated the Precambrian rocks in Sandusky County in 1927, and these rocks were found to be like those in the well at Findlay (Wasson, 1932).

George Hubbard (1932) wrote a summary of what was known about the Precambrian rocks under Ohio, related them to the Precambrian exposed "farther north," and also discussed possible mineral resources which might be obtained from them. This paper should be read with much scepticism; it is undocumented except for three footnotes, it contains mostly vague generalities, and the well locations given in it are anything but exact.

Carl Lamey (Stout and Lamey, 1940) examined the cuttings from the Vance well in Delaware County and determined that they were of a gneiss complex. His work represents the first complete mineralogical and petrological study of well cuttings of Precambrian rocks from Ohio.

MINERALOGY AND PETROLOGY OF ROCK TYPES

HOPKINS WELL

The Hopkins well in Union Township of Fayette County (fig. 1 and table 1) penetrated 1163 feet of Precambrian rocks, of which 82 feet was cored. These Precambrian rocks have been divided into the following four types for purposes of description: granite pegmatite, amphibolite, marble with calc-silicate hornfels, and pyroxene hornfels (fig. 2). The calc-silicate hornfels, which is here grouped with the marble, occurs in thin zones in the marble and is comprised primarily of grossularite and vesuvianite, whereas the pyroxene hornfels occurs in thick units and is composed predominantly of diopside.

Granite Pegmatite

Granite pegmatite was cored from a depth of 4606-4608 feet and is present in well cuttings at the following depths: 3580-3585, 3630-3642, 4445-4450, 4515-4525, 4560-4575, and 4630-4665 feet.

Megascopic description. - The pegmatite (fig. 3) is pink, coarse to medium grained, and contains predominantly large salmon-pink microcline grains ranging from 12 to 25 mm in length. Between the large microcline grains are transluscent white quartz grains and anhedral plagioclase grains averaging 6 mm in diameter. Veins of muscovite (fig. 3) extend through the rock, and a trace of small red garnet is disseminated throughout it.

Microscopic description. - Three thin sections of the granite pegmatite were studied: one from near the middle of the pegmatite core and the other two from the contact between the pegmatite and the overlying amphibolite. The essential minerals of the pegmatite are microcline, albite (Ab_9 to Ab_{10}), quartz, and muscovite; the accessory mineral is spessartite; secondary minerals are calcite and sericite (fig. 4). Feldspar constitutes about two-thirds of the sections; quartz and muscovite make up most of the remainder. Microcline, which comprises the largest grains present and occurs in subhedral grains as much as 18 mm in diameter, exhibits excellent grid twinning of albite and pericline twins and contains inclusions of both quartz and muscovite. The large microcline grains are surrounded by subhedral grains of quartz and albite. The albite, most of which is in graphic intergrowths with quartz (fig. 4), occurs in grains ranging from 0.2 to 8 mm in diameter and has well developed albite twinning. Near the contact of the pegmatite with the amphibolite, the amount of microcline decreases to less than 1 percent and that of albite increases to about 57 percent.

Muscovite is present in veins in which it is intimately associated with quartz. The muscovite plates, some of which include quartz, range in length from 0.53 to 1.43 mm and are oriented with their long axes parallel to the length of the veins. Small euhedral garnets are included in both microcline and albite. Sericite and calcite, the only alteration minerals present, developed along twinning planes and fractures in both the plagioclase and microcline.

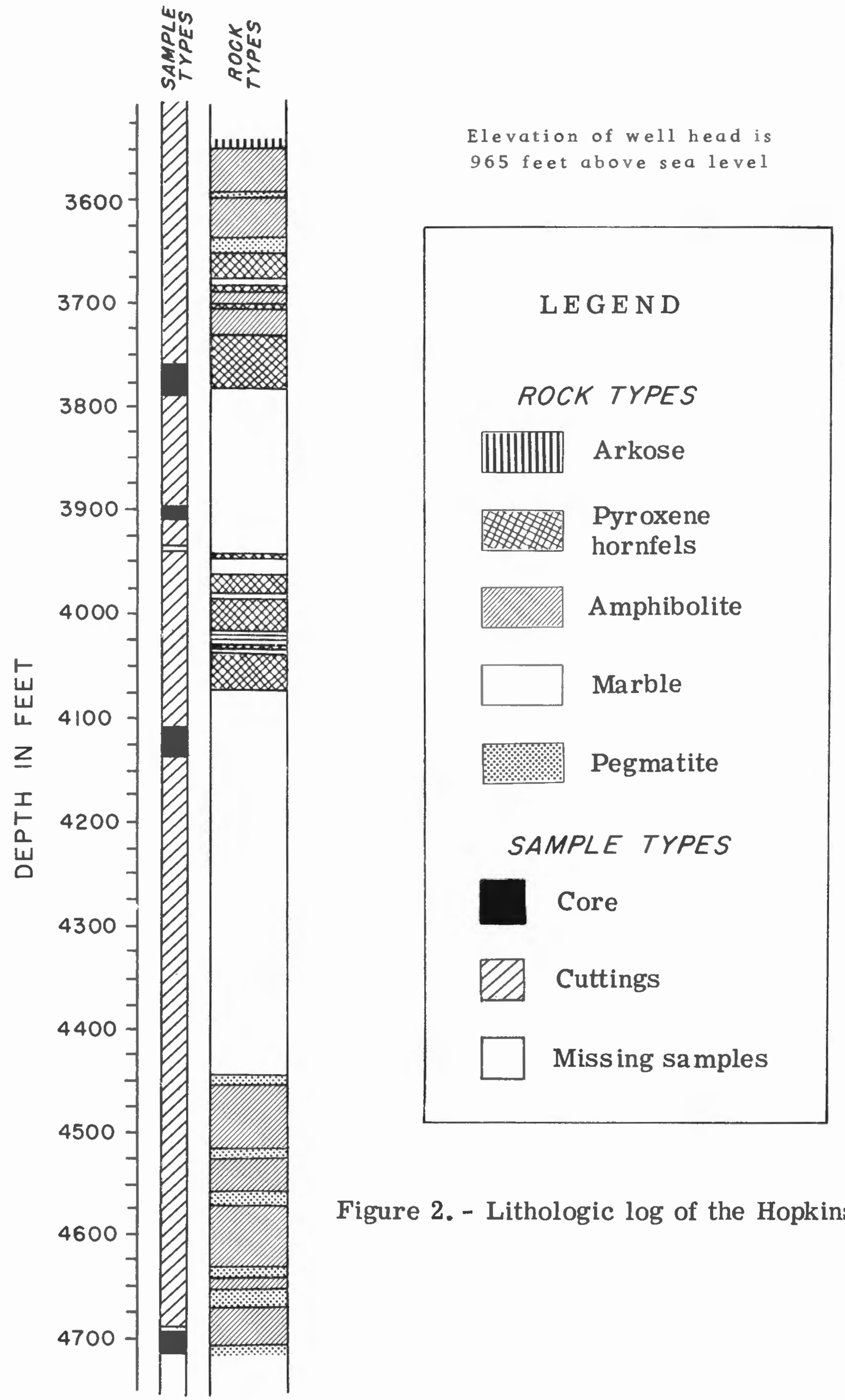

Figure 2. - Lithologic log of the Hopkins well.

Figure 3. - Photograph of granite pegmatite from the Hopkins well. Major portion of the rock is salmon-pink microcline. The pegmatite is cut by veins of muscovite and quartz.

The scale shown in this photograph and in photographs on pages 11, 13, 23, 30, 34, and 37 is in inches.

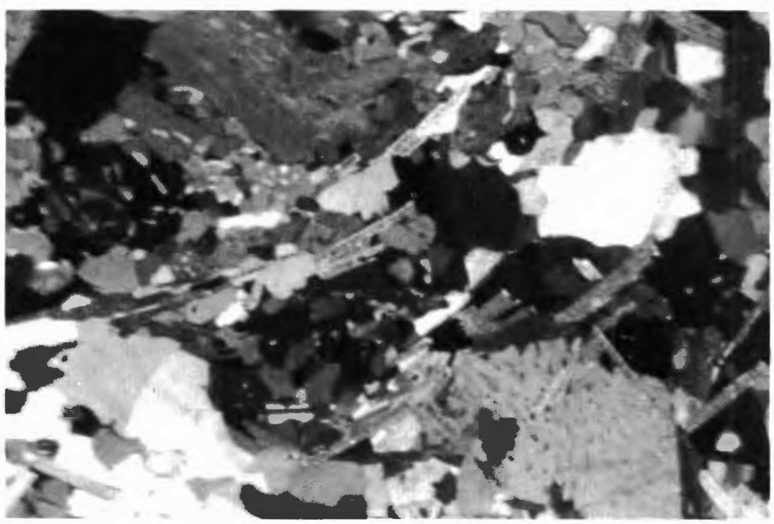

Figure 4. - Photomicrograph of granite pegmatite from the Hopkins well. This portion of the pegmatite contains much micrographic intergrowth of albite and quartz. The lath-shaped grains are muscovite and the large solid white or black grains are quartz. (Crossed nicols, X 32)

TABLE 3. - PERCENTAGES OF MINERALS IN THE ROCK TYPES IN THE CORE OF THE HOPKINS WELL

Minerals	Granite pegmatite	Amphibolite	Marble and calc-silicate hornfels	Pyroxene hornfels
Pyrite	--	--	tr. -2	0-tr.
Pyrrhotite	--	--	0. 6-9	0. 5-5
Chalcopyrite	--	--	--	tr. -1
Quartz	22-32	0-1. 4	--	--
Hematite	--	--	--	tr. -7
Ilmenite	--	--	0-tr.	--
Leucoxene	--	--	2-5	0-tr.
Rutile	--	--	0-tr.	0-tr.
Magnetite	--	5-6	0-tr.	--
Calcite	tr. -1. 3	0-tr.	5-89	0-10
Dolomite	--	--	--	0-4
Apatite	--	7-7. 6	--	0-1
Microcline	1-36	--	--	tr. -32
Albite	21-57	--	--	--
Oligoclase	--	19-30	--	--
Diopside	--	--	2-52	71-91
Anthophyllite	--	--	tr. -10	--
Cordierite	--	--	tr. -27	--
Hastingsite	--	--	0-2	tr. -2
Hornblende	--	47-65	--	--
Spessartite	0-tr.	--	--	--
Grossularite	--	--	1-29	1-11
Vesuvianite	--	--	tr. -42	tr. -5
Zircon	--	0-1	--	--
Epidote	--	--	tr. -2	4-12
Sphene	--	--	--	0-tr.
Muscovite	3-10	--	tr. -14	--
Biotite	--	2-14	--	0-1
Antigorite	--	--	tr. -23	0-tr.

Petrogenesis. - The pegmatite probably was formed by late emanations that came from a granitic body located at a greater depth. The emanations contained abundant albite, microcline, and quartz and less abundant muscovite and garnet. The size and excellent form of the microcline indicate that it began to crystallize first and continued until all the other components had crystallized. Soon after the microcline began crystallizing, albite began, and finally quartz, garnet, and muscovite started to crystallize together. When these last minerals started to crystallize, both microcline and albite were still forming, resulting in albite and quartz being graphically intergrown and large grains of quartz being included by the microcline. After the pegmatite had almost completely crystallized, more fluids very rich in Si, Al, K, and H_2O were injected from the granitic intrusive into the pegmatite, and as these fluids were penetrating the rock, muscovite crystallized and grew with its long axes parallel to the length of the veins in which the fluids were moving. A little quartz crystallized before the muscovite had completely crystallized, as shown by inclusions of quartz in the muscovite; however, most of the quartz formed last and filled in around the muscovite plates in the veins. Very late fluids of the hypothermal stage emanating from the granitic intrusive probably altered some of the feldspar to sericite and calcite.

Amphibolite

Amphibolite was cored from a depth of 4694-4706 feet, and amphibolite fragments were obtained from well cuttings from the following depths: 3545-3630, 3690-3725, and 4450-4689 feet.

Megascopic description. - The amphibolite is a dark gray to black, medium- to fine-grained rock whose major constituents are greenish-black hornblende, biotite, and white plagioclase (fig. 5). The plagioclase constitutes about 20 percent of the rock and occurs in lenses whose long axes are also parallel, thus giving a foliation which can be observed only on smoothly cut surfaces.

Microscopic description. - Six thin sections were cut from the amphibolite in the core, two of which are from the contact of the amphibolite with the underlying pegmatite. The other four are from various distances from the pegmatite to show the changes in mineral assemblages.

The amphibolite is medium grained and hypautomorphic granular. It contains poorly defined lenses of oligoclase whose long axes, as much as 6 mm long, are parallel, and together with alined laths of hornblende define a foliation in the rock. The essential minerals are hornblende and oligoclase; accessory minerals are apatite, biotite, magnetite, ilmenite, and spessartite; alteration minerals are penninite, calcite, and sericite (figs. 6-8). Hornblende occurs as elongate grains ranging in length from 0.04 to 1.17 mm and contains numerous inclusions of biotite, magnetite, and oligoclase. It constitutes about two-thirds of most of the rock; however, near the pegmatite contact the percentage of hornblende decreases to a little less than 50 percent. Oligoclase is next in abundance and occurs in poorly defined lenses which constitute approximately 25 percent of the rock. The lenses have their long axes parallel and are composed of subhedral grains of oligoclase ranging from 0.01 to 2.35 mm in diameter. The oligoclase shows good albite and pericline twinning, includes hornblende and biotite, and is poorly zoned with the centers of the grains more calcic than the edges. Biotite plates ranging from 0.03 to 0.78 mm in length are scattered throughout the rock, and the percentage of biotite increases notably from an average of about 3 percent to approximately 14 percent near the pegmatite contact. The content of apatite, which occurs in euhedral grains ranging from 0.04 to 0.59 mm in diameter disseminated throughout the rock, is uniformly about 7 percent. Magnetite occurs both as small inclusions in biotite, hornblende, and apatite and as large irregularly shaped anhedral grains ranging from 0.06 to 1.56 mm in diameter, many of which include euhedral apatite, hornblende, and biotite and appear to fill in between the other minerals. Several small late quartz veins cut across the amphibolite. Near the contact of the amphibolite and the pegmatite the amphibolite contains 0.5 percent spessartite, a trace of sericite in the twinning planes of the oligoclase, and several areas of penninite (fig. 9) which appear to have formed as a result of the alteration of biotite.

Heavy and light mineral fractions from each of the three intervals of amphibolite chips in the well were examined under the polarizing microscope. In the interval of 4450-4689 feet, oligoclase comprises about 30 percent of the rock, but near the contact of the overlying marble the oligoclase decreases to 10 percent. Hornblende varies from 56 to 25 percent depending on the amount of augite and hypersthene present; the higher the percentage of hornblende the lower is the percentage of pyroxene. Apatite remains at a constant 7 to 8 percent throughout the rock except near the contact of the overlying marble, where it increases to 10 percent. Magnetite, ilmenite, pyrite, and leucoxene are concentrated in certain intervals, particularly near the marble-amphibolite contact. Near the contact of each pegmatite penetrating the amphibolite, the biotite content of the amphibolite noticeably increases and some garnet is present.

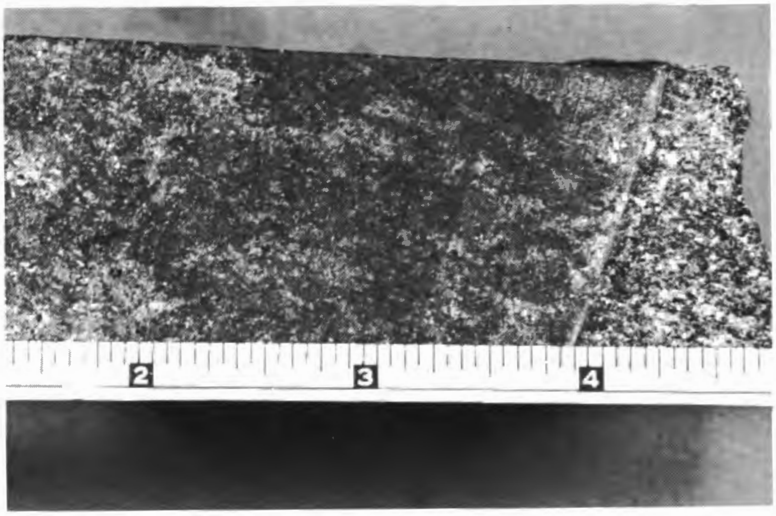

Figure 5. - Photograph of amphibolite from the Hopkins well, with poorly defined foliation shown by augen of feldspar.

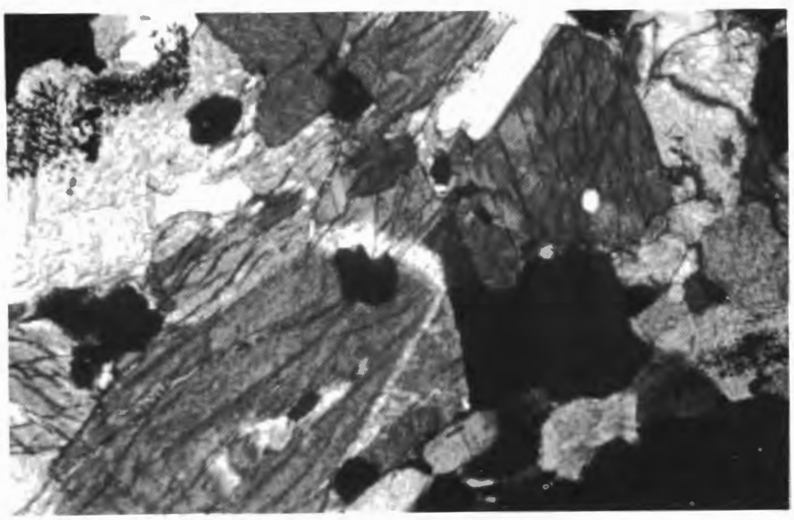

Figure 6. - Photomicrograph of amphibolite from the Hopkins well. The large grains showing cleavage cracks are hornblende. Small dark hexagonal grains included in the hornblende to the left of the center of the photomicrograph, the large hexagonal grain almost at extinction just to the right of the center, and smaller elongate gray six-sided grains near the bottom center of the photomicrograph are all apatite. The large dark area in the lower right-hand corner is feldspar at extinction. (Crossed nicols, X 100)

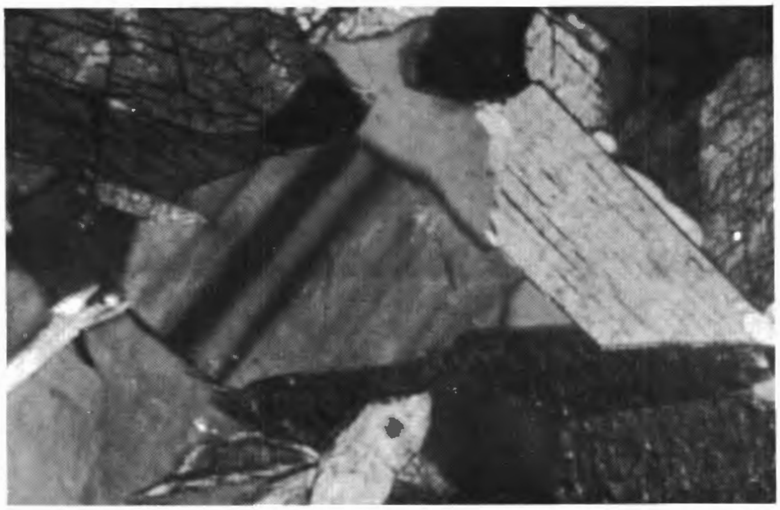

Figure 7. - Photomicrograph of amphibolite from the Hopkins well. The central portion is oligoclase showing albite twinning. Hornblende exhibiting good cleavage is in the upper right- and left-hand corners. The dark mottled lath-shaped grain in the lower right-hand corner is biotite, and at the bottom center is a six-sided elongate grain of apatite. (Crossed nicols, X 100)

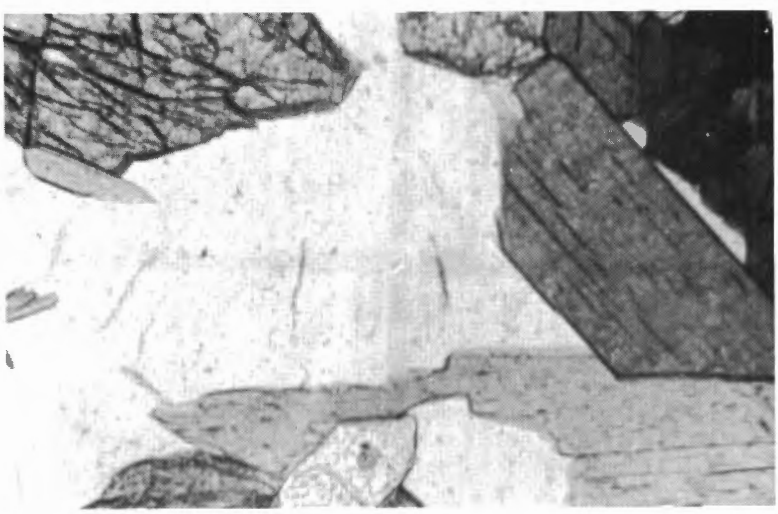

Figure 8. - Photomicrograph of amphibolite from the Hopkins well. Same as figure 7 under uncrossed nicols. The grain of apatite at the bottom center shows its characteristic shape and surface texture. (Plain light, X 100)

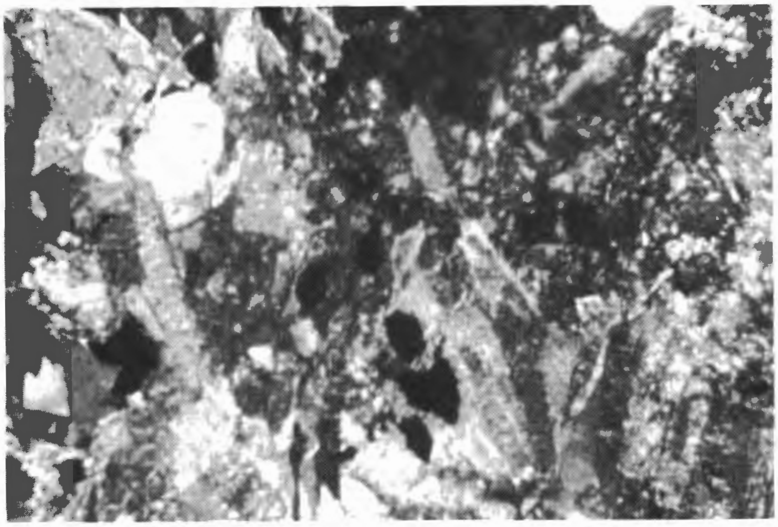

Figure 9. - Photomicrograph of amphibolite from the Hopkins well near the contact with granite pegmatite. The major portion of the photomicrograph is a mass of penninite in which are grains of biotite. The white or black grains to the left of the center are feldspar; some at extinction. (Crossed nicols, X 100)

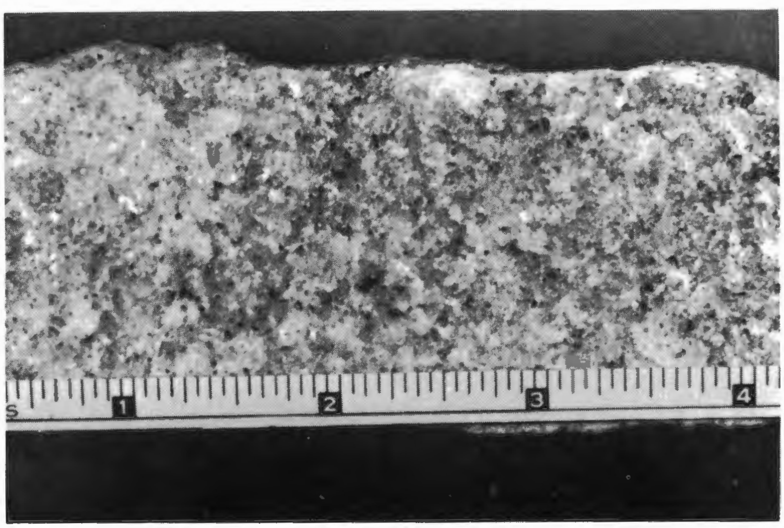

Figure 10. - Photograph of core of marble from the Hopkins well. This portion of the core contains only a few scattered silicate minerals in the calcite.

The amphibolite from the interval 3690-3725 feet, unlike the lower amphibolite, contains almost no oligoclase, but instead it contains 23 percent microcline. In this amphibolite the hornblende content is only 11 percent, whereas the biotite content is 53 percent.

The amphibolite from the interval 3545-3630 feet contains oligoclase and only a trace of potash feldspar. The amount of oligoclase, 36 to 55 percent, is higher than that in the lowermost amphibolite in the well, whereas the apatite content varies between 7 and 9 percent, much like the amphibolite near the bottom of the well. The hornblende percentage is relatively low, ranging between 36 and 12 percent. Enstatite and diopside are present throughout the amphibolite, and a considerable amount of hematite is present near the top of the interval.

Petrogenesis. - The mineralogy of the amphibolites in this well indicates two generic types. The amphibolite in the well core and that in the well samples from the intervals 4450-4689 and 3545-3630 feet is ortho-amphibolite, whereas the amphibolite in the interval 3690-3725 feet is a para-amphibolite

The ortho-amphibolite was derived from a basic igneous rock, most likely a basalt or gabbro. The lines of evidence for this statement are as follows:

1. Occurrence of common normal zoning in plagioclase (Heinrich, 1956, p. 225).
2. General absence or subordination of bands, particularly biotite-, epidote-, or quartz-rich bands (Heinrich, 1956, p. 225).
3. Hornblende and plagioclase tend to be somewhat equally abundant (Williams, Turner, and Gilbert, 1954, p. 241).
4. Quartz and biotite are minor minerals (Williams, Turner, and Gilbert, 1954, p. 242).

The para-amphibolite was derived most likely from an argillaceous sandstone. The evidence for this genesis is as follows:

1. Abundance of biotite or microcline (Heinrich, 1956, p. 256).
2. Lateral gradation into metasedimentary rocks such as marble (Heinrich, 1956, p. 256).
3. Plagioclase is far less abundant than hornblende, (Williams, Turner, and Gilbert, 1954, p. 243).

The hornblende, oligoclase, biotite, apatite, microcline, and pyroxenes are the primary metamorphic minerals. The hornblende was the first mineral to form, followed shortly by biotite, and then oligoclase or microcline. As the rock was metamorphosed, the sodium, calcium, and silica which combined to form oligoclase must have migrated to centers of accumulation where the oligoclase grew as concretionary type masses which were flattened by surrounding pressures as they grew. The last of the primary metamorphic minerals to form was probably apatite, since it occurs generally as elongated euhedral grains between hornblende and oligoclase. The sulfides, ilmenite, and magnetite, representing a late ore stage of metamorphism, were brought into the amphibolite in late hydrothermal gases and vapors from a cooling granitic intrusive which was injected simultaneously with, or very soon after, regional metamorphism. The percentage of opaque minerals is higher near contacts of rock types and particularly near areas intruded by pegmatite veins. This is evidence that the late hydrothermal gases used these contact planes as their chief conduits and diffused into the rock from these channels. Much of the escaping water vapor from the cooling granite and pegmatite entered into the chemical constitution of hornblende near the pegmatite contacts and converted some of it to biotite. Further action of gaseous vapors of the cooling granite and pegmatite converted some of the biotite to penninite and formed a little sericite on the plagioclase feldspar. The late quartz veins cutting the rock were introduced at the time the pegmatite veins were injected.

Marble and Calc-Silicate Hornfels

Marble and calc-silicate hornfels were cored from the following depths: 3751-3752, 3892-3902, and 4102-4135 feet. These rocks were also obtained in well cuttings from the following depths: 3670-3680, 3777-3935, 3940-3960, 3980-3985, 4055-4060, and 4075-4435 feet.

Megascopic description. - The core and cuttings show a complete gradation between calc-silicate hornfels and calcite marble. The rock is coarse grained, nonfoliated, and is not uniform in mineral content. It is made up of three predominant varieties of rock which are gradational with each other and which occur repeatedly. Calcite marble, which is the most prevalent type (fig. 10), is white and is composed of large twinned grains of calcite with a few smaller grains of dark green diopside. Narrow zones of two varieties of calc-silicates are interspersed in the marble; one variety is in layers from 3 to 9 inches thick and is rich in grossularite and olive-green vesuvianite that occurs in spheroidal masses, whereas the other variety contains abundant pyrrhotite, ranges from 3 to 12 inches in thickness, and is dark gray.

Microscopic description. - Seventeen thin sections of the marble and calc-silicate core were cut; two are from the contact of the marble with a pyroxene hornfels, and fifteen are from different places in the marble and calc-silicate hornfels. The silicate minerals are not evenly distributed in the marble; some silicate minerals occur as single grains included in calcite, but most of them occur in narrow zones through the rock or in aggregates between the calcite grains (fig. 11). Hence, some sections are predominantly silicates, whereas other sections are as much as 89 percent calcite.

The marble and calc-silicate hornfels is medium to coarse grained and has a hornfelsic texture. Calcite is the most predominant mineral, comprising 42-89 percent of the rock, exclusive of the thin zones containing high percentages of silicates. The calcite grains are anhedral, have a mosaic fabric, range from 0.09 to 2.35 mm in diameter and include diopside, grossularite, muscovite, antigorite, vesuvianite, and pyrrhotite. Euhedral to subhedral diopside comprises 2 to 52 percent of the rock. The centers of the large grains of diopside are altered to small grains of epidote and a trace of antigorite (figs. 12-14). Grossularite comprises as much as 29 percent of the rock and occurs in anhedral grains ranging in diameter from 0.03 to 0.69 mm. It is associated with vesuvianite, includes or partially surrounds some grains of calcite, and includes diopside. The centers of some large grains of garnet are much altered to antigorite, and in several areas in the rock, garnet and calcite are micrographically intergrown. Vesuvianite in these rocks is very trashy appearing (figs. 15-16), with anomalous gray-green to ultra-blue interference colors (fig. 17). It comprises as much as 42 percent of the rock in the silicate-rich zones of the marble, but in other parts it comprises no more than 7 percent. In the calcite-rich portions of the rock the vesuvianite ranges in diameter from 0.04 to 0.19 mm, includes small grains of pyrrhotite and muscovite, completely surrounds some small grains of calcite, and appears to have replaced some of the grossularite. The vesuvianite grains in the silicate portions of the rock range up to 5.89 mm in diameter and include many grains of diopside, muscovite, calcite, and grossularite. Antigorite comprises as much as 23 percent of the rock; the silicate-rich zones are the areas of higher antigorite concentration.

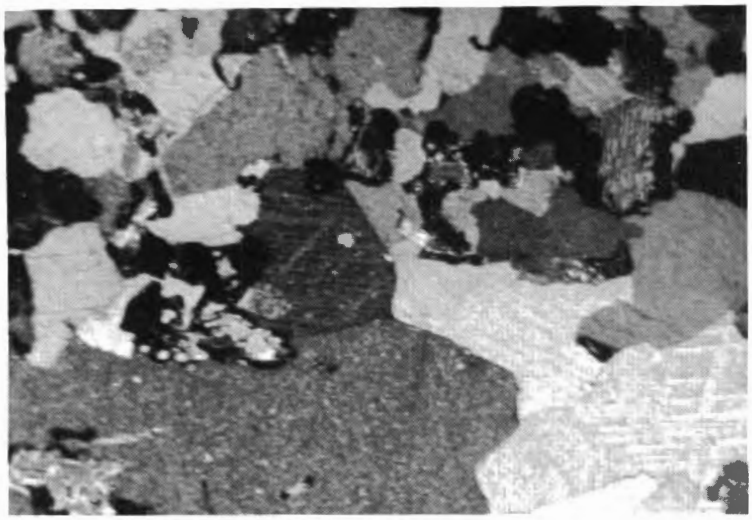

Figure 11. - Photomicrograph of marble from the Hopkins well showing texture of calcite-rich portions. Black areas in the upper half of the photomicrograph are sulfide minerals, principally pyrrhotite and chalcopyrite. (Crossed nicols, X 32)

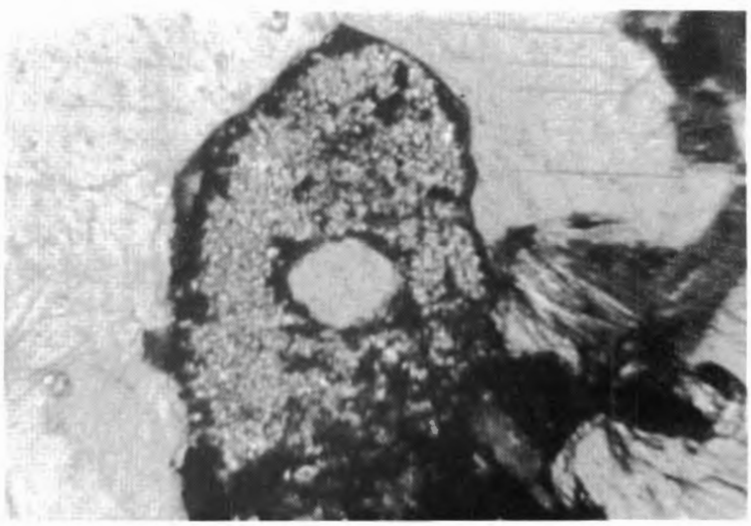

Figure 12. - Photomicrograph of a grain of altered diopside in marble from the Hopkins well. In the center of the grain is calcite which probably was included originally in the diopside grain. The rest of the grain consists predominantly of very small grains of epidote, and small patches of antigorite which appears black. The entire grain is bordered by antigorite. (Crossed nicols, X 120)

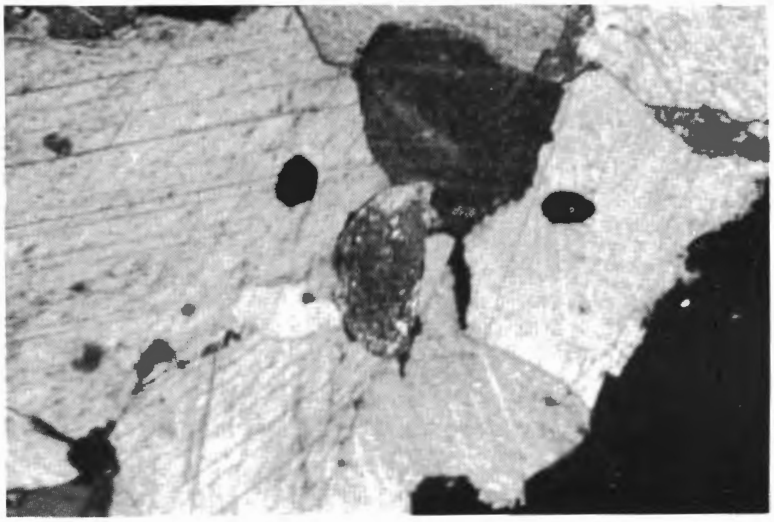

Figure 13. - Photomicrograph of marble from the Hopkins well showing an altered diopside grain. (Crossed nicols, X 32)

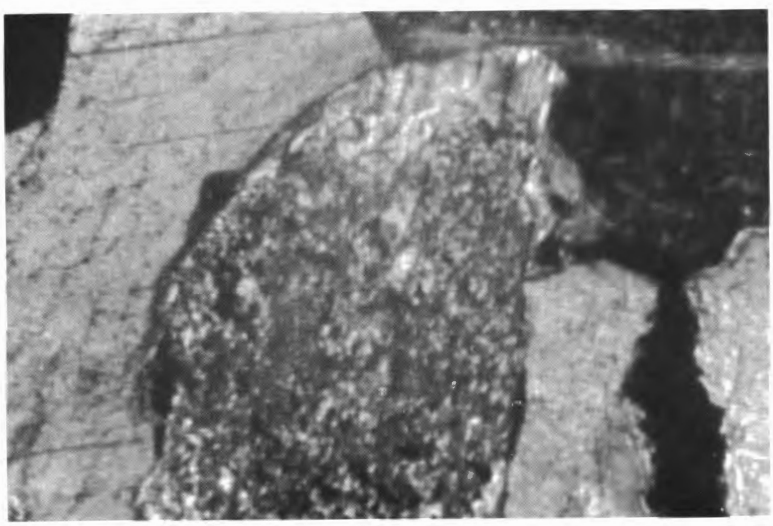

Figure 14. - Photomicrograph of same diopside grain from the Hopkins well as is shown in figure 13. The center of the grain has completely altered to a mass of small epidote grains. Near the edges, particularly the top edge, are remnants of the diopside exhibiting cleavage. (Crossed nicols, X 100)

Figure 15. - Photomicrograph of vesuvianite from a calc-silicate zone in the marble from the Hopkins well. The entire field is anomalous olive-green vesuvianite containing small inclusions of diopside and calcite. (Crossed nicols, X 32)

Figure 16. - Photomicrograph of vesuvianite from a calc-silicate zone in the marble from the Hopkins well. The entire field is vesuvianite, full of small grains of calcite and diopside. (Crossed nicols, X 32)

The antigorite occurs in felted masses of small fibers and is present as a replacement mineral in or around diopside, grossularite, and vesuvianite (fig. 18), and as late veins cutting the marble (fig. 19). Hastingsite is present as elongate grains ranging from 0.06 to 1.6 mm in length in the silicate-rich zones. Muscovite comprises as much as 14 percent of the rock and occurs as plates ranging in diameter from 0.04 to 0.59 mm (fig. 20). Areas of anthophyllite range from 0.11 to 0.69 mm in diameter and are composed of a mass of small fibers. Tremolite, in the marble, occurs as small needles radiating into the calcite grains from the centers of silicate mineral concentration. Pyrrhotite comprises as much as 9 percent of the rock; it occurs as anhedral grains ranging from 0.03 to 0.59 mm in diameter, many of which occur in clusters intimately associated with diopside and garnet. The pyrrhotite was the last mineral to develop and grains of it penetrate cracks in mineral grains adjoining the pyrrhotite regardless of the species of the mineral (fig. 21).

The well cuttings show marble, with silicate-rich zones interspersed through it, like that in the core. The predominant minerals in the silicate-rich zones are vesuvianite, which ranges to 40 percent, and diopside, which ranges to 35 percent. The calcite-rich zones contain about 85 percent calcite and 15 percent diopside.

Petrogenesis. - The marble and calc-silicate hornfels was probably originally a dolomitic limestone with thin argillaceous interbeds which was metamorphosed to the hornblende hornfels facies (Fyfe, Turner, and Verhoogan, 1958, p. 205) by heat from an intrusive granitic body and regional pressures. The calcite grains in the limestone were recrystallized into sharply defined well-twinned grains of calcite, and the interstitial argillaceous material in the limestone, together with some carbonate from the limestone, was changed to diopside, grossularite, muscovite, and a little vesuvianite. These silicate minerals had their initial formation between the calcite grains, in the spaces that were occupied by the argillaceous material, and they expanded from these spaces into surrounding areas previously occupied by calcite. Much grossularite, diopside, hastingsite, and some vesuvianite formed in the argillaceous interbeds. After the initial metamorphism of the sedimentary rock, hydrothermal emanations containing fluorine from the cooling granitic intrusive favored the formation of vesuvianite instead of grossularite. As a result of the added water and fluorine, some of the grossularite that had already formed was converted to vesuvianite. This conversion, and the formation of vesuvianite in preference to grossularite, resulted in vesuvianite growing to large grains which included many of the previously formed minerals. The addition of the water caused part of the diopside to alter to epidote; the centers of the large diopside grains were completely altered. Antigorite formed as an alteration mineral from both diopside and grossularite. Final hydrothermal emanations rich in sulfur and iron formed iron sulfides in the rock.

Pyroxene Hornfels

Pyroxene hornfels was cored from a depth of 3752-3777 feet and was recovered in well samples from the following depths: 3640-3670, 3680-3685, 3695-3700, 3935-3940, 3965-4020, and 4035-4070 feet.

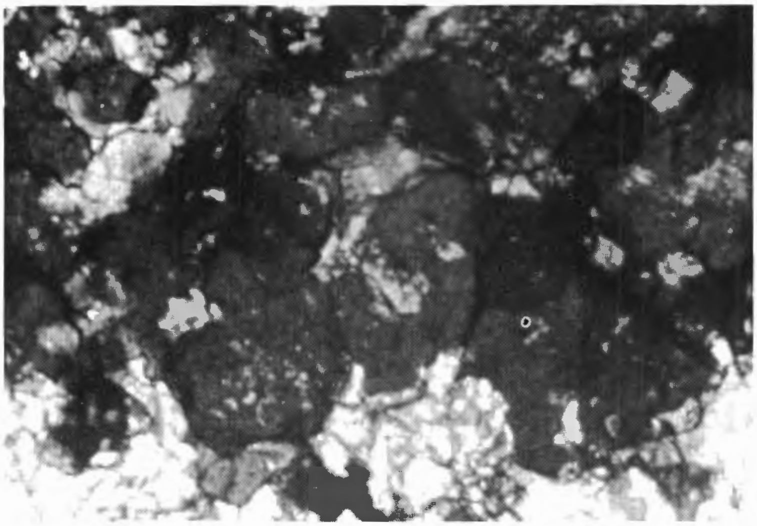

Figure 17. - Photomicrograph of vesuvianite from the Hopkins well showing anomalous olive-gray-green and ultrablue interference colors. Small grains of calcite and diopside are scattered through the vesuvianite. (Crossed nicols, X 32)

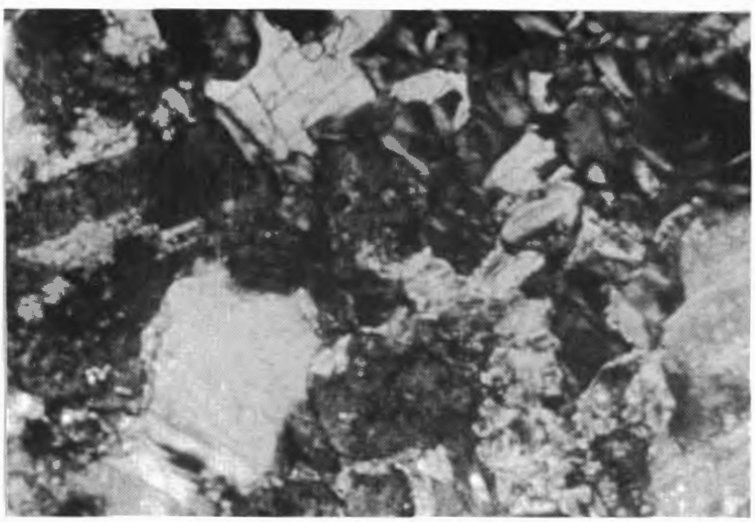

Figure 18. - Photomicrograph of an altered silicate aggregate in the marble of the Hopkins well. The major portion of the photomicrograph that appears dark gray or black is antigorite and chlorite, formed from alteration of diopside, grossularite, and some calcite. A large calcite grain just left of the center at the top has been embayed on all sides during the alteration process. (Crossed nicols, X 100)

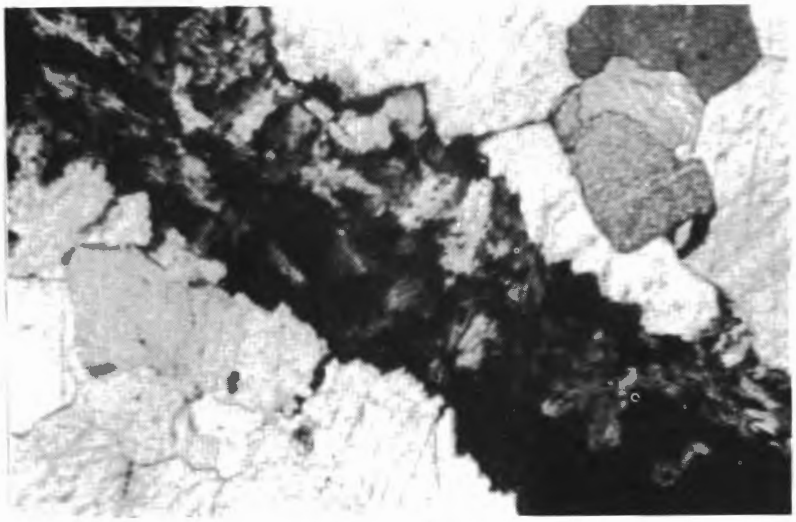

Figure 19. - Photomicrograph of a vein of antigorite cutting the marble in the Hopkins well. (Crossed nicols, X 32)

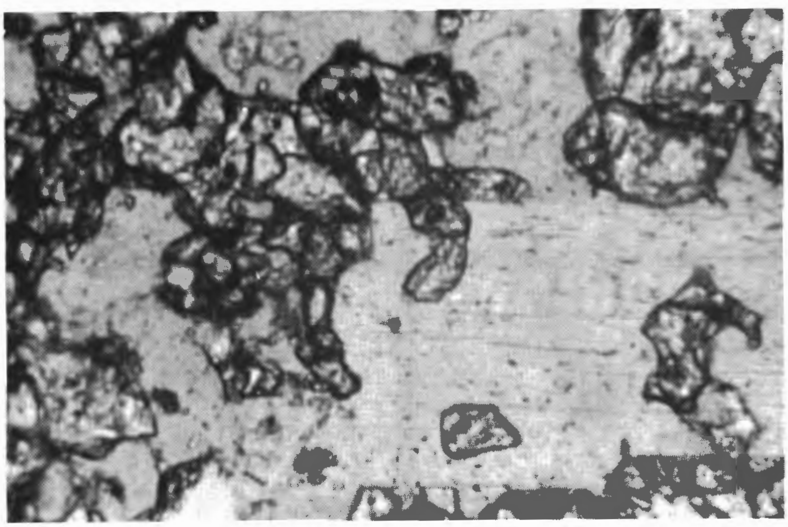

Figure 20. - Photomicrograph of a portion of a calc-silicate hornfels in the marble from the Hopkins well. The light-colored mineral in the lower right-hand side is a large grain of muscovite; the high-index mineral disseminated throughout is grossularite; and the remainder of the area is chlorite. (Crossed nicols, X 32)

Megascopic description. - The pyroxene hornfels is xenomorphic granular, greenish black, and medium to coarse grained with some pyroxene grains as much as 3.5 mm in diameter (fig. 22). The major constituent is very dark greenish-black diopside with a subsidiary amount of transluscent light green epidote surrounding the diopside grains. Pyrrhotite, which includes some chalcopyrite, is scattered throughout the rock but some is concentrated in patches as much as 21 mm in diameter. Randomly scattered through the rock are small irregularly shaped aggregates of white calcite and hastingsite. Several aggregates of microcline 17.5 mm in diameter are surrounded by rose-red garnet and vesuvianite.

Microscopic description. - Six thin sections of pyroxene hornfels were cut: two from the contact of pyroxene hornfels and an underlying marble, and the other four from different intervals in the pyroxene hornfels. The rock is coarse grained, xenomorphic granular, has a mortared fabric, and contains large well-twinned grains of diopside as its main constituent. The large grains of diopside, 0.78 to 3.54 mm in diameter, are surrounded by a matrix composed of small grains of diopside, dolomite, vesuvianite, garnet, pyrrhotite, chalcopyrite, apatite, and hematite and by larger interstitial areas of dolomite, hastingsite, and microcline (figs. 23-24). The diopside comprises 71-91 percent of the rock and contains inclusions of vesuvianite, pyrrhotite, biotite, and epidote. The small diopside grains, ranging from 0.05 to 0.78 mm in diameter, are in the matrix of silicate minerals near the granulated borders of the large diopside grains. Epidote is the major mineral in the matrix, and also the major alteration mineral in the large diopside grains (figs. 25-26), where it occurs predominantly along twinning planes and cleavage cracks. Very small exsolution lamellae of pigeonite occur in the center of many of the large diopside grains (fig. 24). They appear only as black specks in the centers of the grains under a magnification of X 32. Pyrrhotite, which includes some chalcopyrite ranging in diameter from 0.02 to 0.05 mm, is present as anhedral grains ranging from 0.04 to 1.75 mm in diameter. It appears predominantly in interstitial areas between large diopside grains, but some is included in the diopside (figs. 27-28). The content of pyrrhotite increases from 0.5 percent at 3756 feet to 5 percent at 3752 feet. Hematite, present as anhedral grains ranging from 0.02 to 0.78 mm in diameter principally in the interstitial areas associated with pyrrhotite and garnet, likewise increases from a trace at 3756 to 7 percent at 3752 feet. Under high power, the pyrrhotite and hematite both can be seen to penetrate small cracks in minerals adjacent to them regardless of the species of the adjacent mineral (fig. 29). At a depth of 3752.5 feet there is an aggregate of microcline 14 mm in diameter, composed of microcline grains ranging from 0.04 to 0.59 mm in diameter, which shows excellent grid twinning and includes diopside (fig. 30). This aggregate is surrounded by a rim of garnet and vesuvianite grains ranging from 0.12 to 0.78 mm in diameter and two large grains of apatite ranging from 0.70 to 0.78 mm in diameter (figs. 30-31). The vesuvianite in the rim surrounding the microcline contains small inclusions of microcline, small euhedral grains of sphene (fig. 32), and about 1 percent biotite.

Well cuttings of the pyroxene hornfels contain 60-85 percent diopside, 15-30 percent vesuvianite and garnet, and subsidiary amounts of epidote and sulfide minerals.

Petrogenesis. - The pyroxene hornfels was probably originally sandy or siliceous dolomite that was thermally metamorphosed to the hornblende hornfels facies (Fyfe, Turner, and Verhoogan, 1958, p. 205). The rock was initially metamorphosed by heat from a granitic intrusive and heat caused by regional pressures with very little accompanying fluids and gases. Diopside formed as large grains, with some accompanying hastingsite, and small amounts of garnet and calcite. After the initial metamorphism of the dolomite, internal movements granulated the borders of the large diopside grains. Accompanying and following the granulation, fluid and gaseous emanations from the intrusive passed readily through the

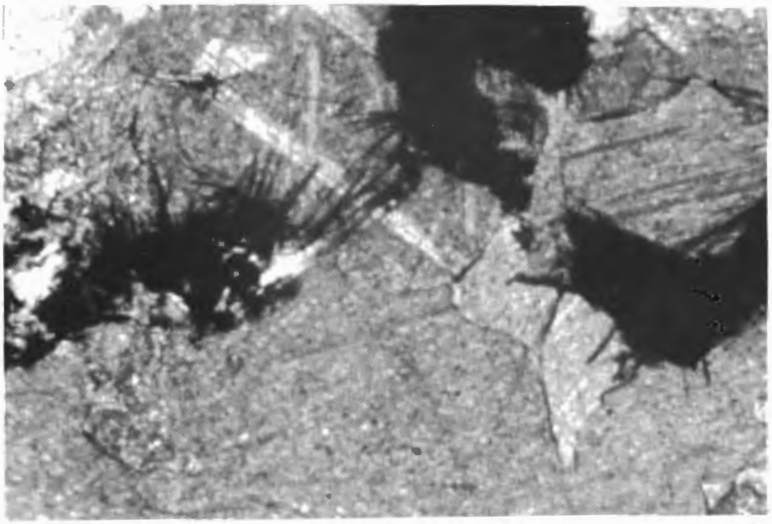

Figure 21. - Photomicrograph of pyrrhotite in marble from the Hopkins well. Note penetration of pyrrhotite into the surrounding calcite grains, which indicates that the pyrrhotite is the younger. (Crossed nicols, X 100)

Figure 22. - Photograph of pyroxene hornfels from the Hopkins well. The parallel marks on the smooth surface of the center of the pyroxene hornfels core are saw marks.

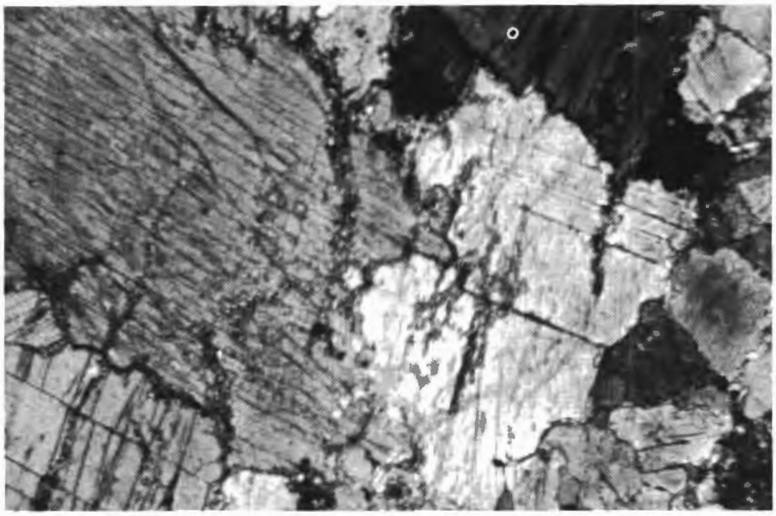

Figure 23. - Photomicrograph of pyroxene hornfels from the Hopkins well. The large grains showing both twinning and cleavage are diopside and the very small grains between the large diopside grains are epidote which altered from the diopside. (Crossed nicols, X 32)

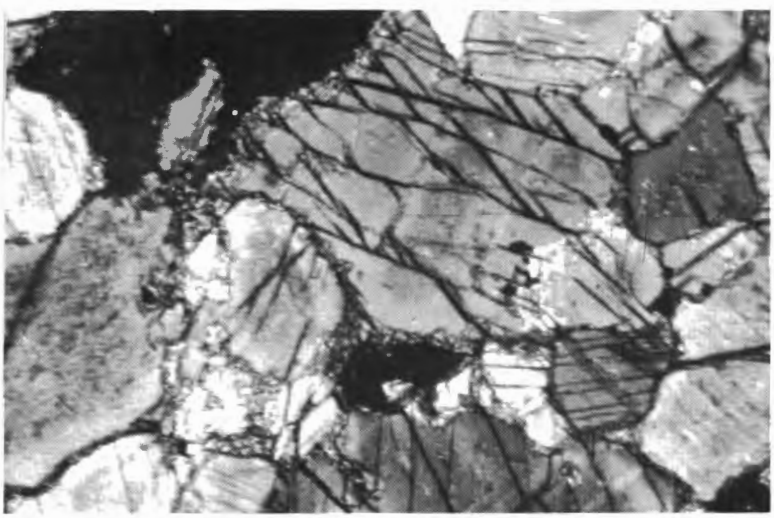

Figure 24. - Photomicrograph of pyroxene hornfels from the Hopkins well. Large plates of diopside show excellent cleavage and are surrounded by small grains of epidote which has altered from the diopside. The center of the large grain of diopside on the left-hand side contains many exsolution lamellae of pigeonite which appear as black specks. (Crossed nicols, X 32)

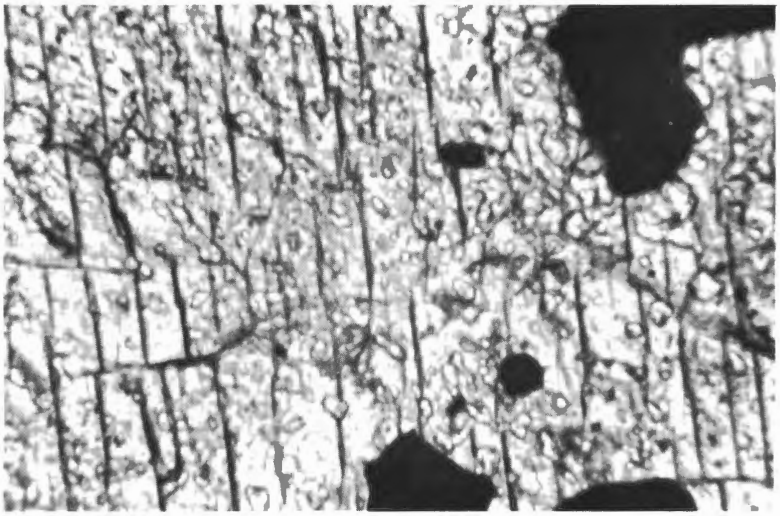

Figure 25. - Photomicrograph of a diopside grain from the Hopkins well, partly altered to epidote. The epidote is the small high relief grains scattered throughout the diopside plate; the black grains on the right are pyrrhotite. (Crossed nicols, X 100)

Figure 26. - Photomicrograph of pyroxene hornfels from the Hopkins well showing a light-colored grain of diopside in the center which has very closely spaced cleavage in relation to the cleavage in the surrounding grains of diopside. (Crossed nicols, X 100)

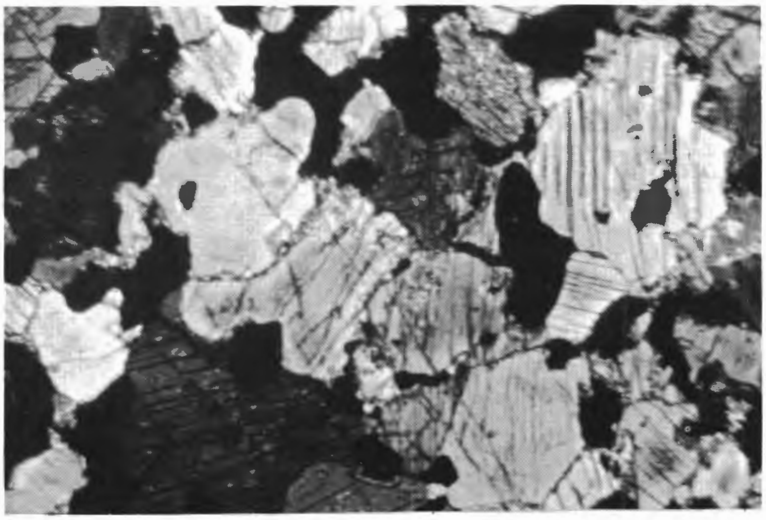

Figure 27. - Photomicrograph of pyroxene hornfels from the Hopkins well showing high percentage of sulfide minerals. The large grains exhibiting cleavage are diopside, the small grains in the cleavage cracks of the diopside and between the diopside grains are epidote, and the opaque grains are pyrrhotite with a trace of chalcopyrite. (Crossed nicols, X 32)

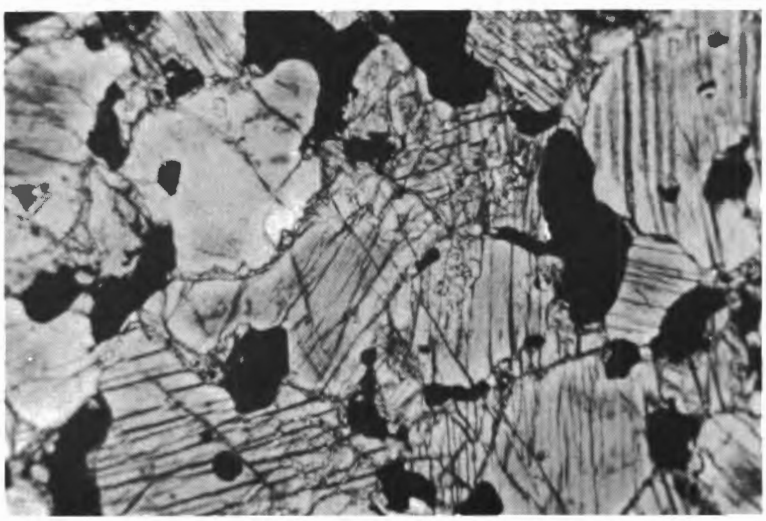

Figure 28. - Photomicrograph of pyroxene hornfels from the Hopkins well showing high percentage of sulfide minerals. Same view as figure 27. (Plain light, X 32)

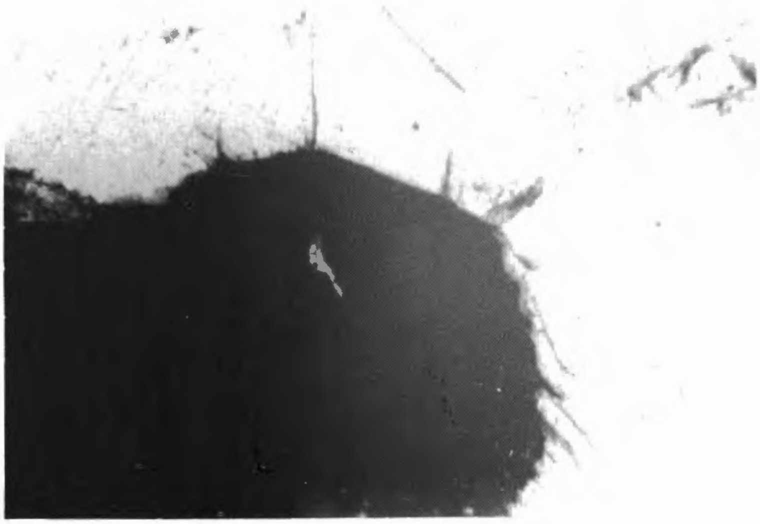

Figure 29. - Photomicrograph of pyroxene hornfels from the Hopkins well showing penetration of pyrrhotite grain into the cracks in the adjoining diopside. (Plain light, X 120)

Figure 30. - Photomicrograph of an aggregate of microcline in pyroxene hornfels from the Hopkins well. Most of the left side is microcline showing grid twinning; at the top center is a corroded vesuvianite grain; and the large dark grains on the right are apatite. (Crossed nicols, X 32)

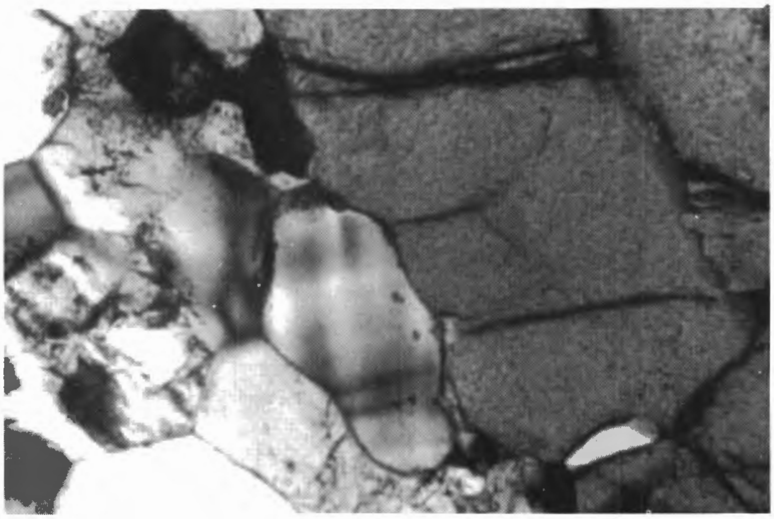

Figure 31. - Photomicrograph showing the border around an aggregate of microcline in the pyroxene hornfels from the Hopkins well. The grain in the center exhibiting grid twinning is microcline, the large dark gray grain to the right is apatite, and the white grains with dark spots in their centers on the left are corroded vesuvianite grains. (Crossed nicols, X 32)

Figure 32. - Photomicrograph of border around an aggregate of microcline in the pyroxene hornfels from the Hopkins well, showing a euhedral grain of sphene in the center. The gray mineral exhibiting cleavage, to the right, is diopside which includes opaque pyrrhotite grains, and the light mineral to the left and surrounding the grain of sphene is microcline. (Plain light, X 120)

interstitial areas around the large diopside grains. Epidote was formed as an alteration mineral of the small fragments of diopside around the edges of the large diopside grains, and of diopside along twinning planes and cleavage cracks in the large grains. Some of the grossularite between the large grains also was altered to antigorite. Hydrothermal emanations rich in sulfur and iron then entered the rock from the cooling intrusive and deposited pyrrhotite with some chalcopyrite. The sulfide minerals began to grow in the interstitial areas between the large diopside grains and then expanded into areas previously occupied by some of the diopside. Continuing emanations from the cooling intrusive rich in oxygen, or ground water passing through the rock, oxidized much of the pyrrhotite to hematite, especially near the contacts of two rock types. Apparently these late gases or the ground water used these contact planes as their primary routes and penetrated the rocks on either side of the contact for only a short distance.

Relative Ages of the Rocks in the Hopkins Well

A sequence of sedimentary rocks consisting of dolomitic limestones with thin argillaceous interbeds, sandy or siliceous dolomite, and argillaceous dolomitic sandstone was deposited and later intruded by a basic igneous rock, probably a basalt or gabbro. Some time after the introduction of the basic igneous rock, the area was subjected to regional metamorphism and a granitic mass was intruded. The sedimentary sequence and the basic igneous rock were metamorphosed to the hornblende hornfels facies; the basalt was changed to ortho-amphibolite, the dolomitic limestone with thin argillaceous interbeds was changed to marble and calc-silicate hornfels, the sandy or siliceous dolomite was converted to pyroxene hornfels, and the argillaceous dolomitic sandstone was converted to para-amphibolite. After the intrusion of the granitic mass, pegmatite dikes and quartz veins whose source was in the granitic body were formed in the ortho-amphibolite and along the contact planes between the amphibolite and the marble-calc-silicate hornfels. These pegmatite dikes have been dated by Dr. Manual N. Bass of the Carnegie Institute, who ran rubidium-strontium dates on muscovite books from the pegmatite and found that the pegmatite was 980 million years old (personal communication).

SMITH WELL

The Smith well in Hinckley Township of Medina County (fig. 1 and table 1) was drilled 110 feet into Precambrian rocks. The bottom 12 feet of the well was cored and the bottom 3 feet of the core was lost in the hole. Before the writer was able to obtain this core for study, 5 of the remaining 9 feet had been lost or used for purposes other than study. The remaining 4 feet of core contained representative samples from each of the rock types cored. For purposes of description the rocks in the core have been divided into two groups: granite gneiss and marble.

Granite Gneiss

Granite gneiss was cored from depths of 7028-7030 and 7035-7037 feet, and was obtained in well samples from 6930-7028 feet.

Megascopic description. - The granitic gneiss is coarse grained and contains several sets of healed fractures (fig. 33). In the well samples and at the top

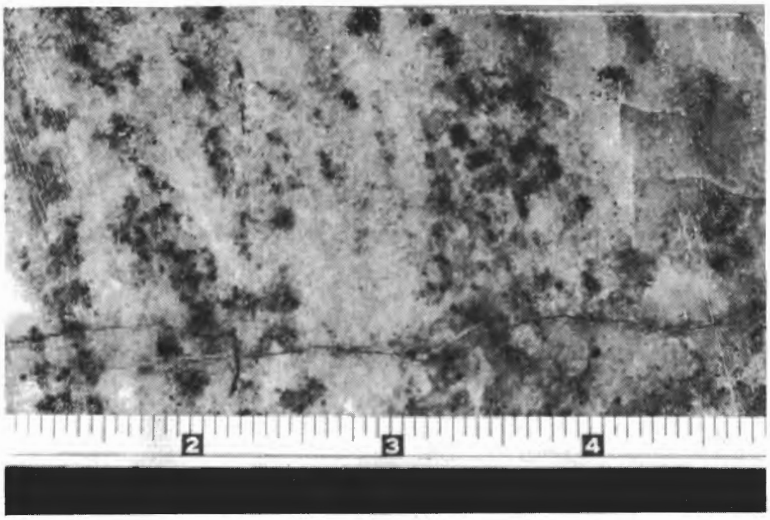

Figure 33. - Photograph of granitic gneiss from the Smith well showing weak banding.

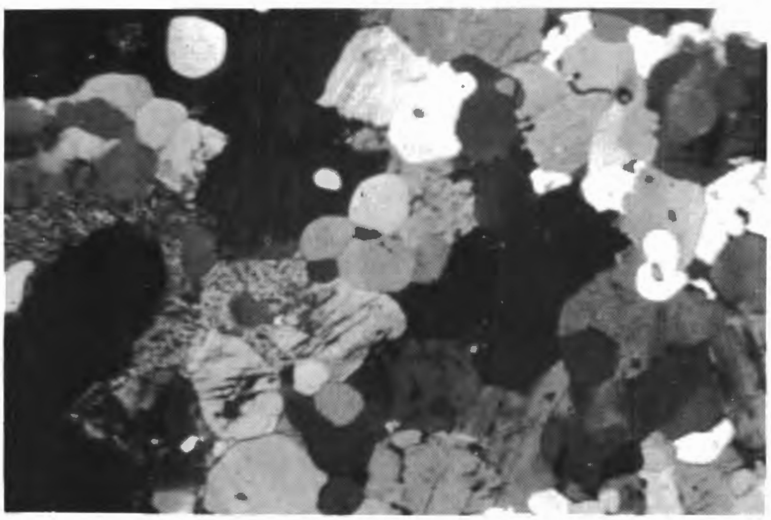

Figure 34. - Photomicrograph of granitic gneiss from the Smith well showing general texture. The medium gray grains scattered throughout are mostly oligoclase and a few are microcline, the large white and black grains are quartz, and the rounded white and light gray grains scattered throughout are blastoporphs of microcline, oligoclase, zircon, and sphene. (Crossed nicols, X 32)

of the core it is composed principally of dark red potassium feldspar cut by bands of chlorite as much as 3.5 mm thick, both crossed by veins of quartz, pyrite, and chlorite. This rock grades downward into granitic gneiss composed of alternating bands of salmon-pink microcline and greenish sausseritized plagioclase in which are thin bands of chlorite as much as 3.5 mm thick. The granite gneiss between the bottom of the marble and the bottom of the core, 7035-7037 feet, is composed principally of green sausseritized plagioclase grains as much as 7 mm in diameter, with minor amounts of quartz, chlorite, and microcline.

Microscopic description. - The rock is coarse grained, subhedral granular, and shows moderate granulation. Oligoclase (An_{16}-An_{19}) comprises from 47 to 74 percent of the rock (table 4), is the major feldspar, and occurs in anhedral

TABLE 4. - PERCENTAGES OF MINERALS IN THE ROCK TYPES OF THE SMITH WELL

Minerals	Marble	Granite gneiss
Pyrite	0-tr.	0-1
Quartz	1-3	23-39
Leucoxene	--	0-tr.
Scheelite	0-tr.	--
Magnetite	0-tr.	--
Calcite	--	tr.-0.5
Dolomite	84-96	tr.-1
Apatite	0-1	tr.-1
Orthoclase	0-tr.	tr.-1
Microcline	--	1-12
Oligoclase	--	47-74
Zircon	0-tr.	0-tr.
Epidote	--	0-tr.
Sphene	--	0-tr.
Sericite	--	tr.-0.5
Biotite	--	0-tr.
Chlorite	1-15	1-2

grains ranging from 0.06 to 4.70 mm in diameter. It includes zircon, apatite, sphene, quartz, microcline, and pyrite, and has altered in part to chlorite, calcite, and epidote, particularly along twinning planes and cleavage cracks. Quartz, which is strained, comprises 23 to 39 percent of the rock, occurs in large anhedral grains ranging from 0.03 to 4.8 mm in diameter, and contains inclusions of microcline, oligoclase, zircon and sphene. Microcline occurs in anhedral grains, comprises as much as 12 percent of the rock, shows excellent grid twinning, and occurs principally between the oligoclase and quartz grains (figs. 34-37). All of the feldspar has altered in part to sericite, chlorite, and epidote, and small fractures that penetrate the rock have been filled with chlorite and pyrite. Pyrite, which occurs in anhedral grains ranging from 0.03 to 0.57 mm in diameter, is scattered through the rock but appears principally in veins associated with chlorite.

Petrogenesis. - The exact genesis of the granitic gneiss cannot be determined from the small pieces of gneiss that were obtained in the core. The gneiss could possibly be a metamorphosed granitic rock, a granitic rock with primary flow structure, a granitized sediment, or a metamorphosed sediment. It is apparent, however, that in the later stages of its formation, the rock was badly fractured. Late hydrothermal solutions, rich in iron and sulfur, used these fractures as channels and altered much of the feldspar to chlorite and calcite, part of the biotite to chlorite, and filled the fractures with chlorite and pyrite.

Figure 35. - Photomicrograph of granitic gneiss from the Smith well showing microcline, oligoclase, and quartz. The central portion is microcline and oligoclase, and the right and left sides are quartz and oligoclase. It can be seen that the microcline crystallized after the oligoclase and did not exsolve from it (Crossed nicols, X 32)

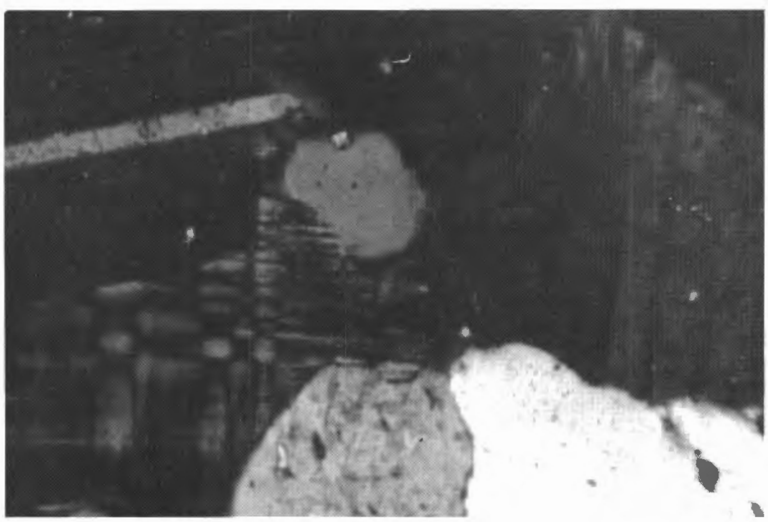

Figure 36. - Photomicrograph of granitic gneiss from the Smith well showing microcline filling around oligoclase laths, indicating that it crystallized after the oligoclase and did not exsolve from it. Same view as figure 35. (Crossed nicols, X 100)

Marble

Marble was cored in the interval 7033-7035.5 feet.

Megascopic description. - The marble is medium-grained, vuggy dolomite that contains veinlets of chlorite in the top 1.5 feet of the interval (fig. 38). The upper one-half foot of the marble contains rows of vugs, lined with rhombohedral crystals of brown dolomite, which demarcate old fractures. The lower part of the core is composed of as much as 96 percent medium-grained dolomite in anhedral grains that are as much as 3.5 mm in diameter and are arranged in a mosaic fabric. This part of the core also contains cavities into which dolomite rhombs have grown. A very thin fracture that cuts this portion of the marble, as well as the cavities on either side of the fracture, is filled with chlorite.

Microscopic description. - Four thin sections were cut from the marble in this core: three from a chloritic portion near the top and one from the bottom. The rock is medium grained and hornfelsic. Anhedral dolomite grains, ranging in diameter from 0.05 to 2.35 mm, comprise 84-96 percent of the rock and contain inclusions of apatite, zircon, and pyrite. The upper portion of the rock contains 5-15 percent chlorite in bifurcating veinlets (fig. 39). These veinlets are both pulled apart in places and broken by many small faults which do not extend more than 2 or 3 cm and are randomly oriented (fig. 39); recrystallized dolomite has filled in the fractures. Quartz comprises as much as 2 percent of the rock, occurs in anhedral grains ranging from 0.07 to 0.39 mm in diameter, and in places includes many small tetrahedral pyramids of scheelite (fig. 40). This scheelite has negative (-) elongation, a birefringence between 0.015 and 0.020, and it fluoresces under ultraviolet light. The marble in the lower part of the core contains only 1 percent chlorite and 1 percent included euhedral apatite grains which range from 0.11 to 0.47 mm in diameter. A trace of pyrite in grains 0.02 to 0.03 mm in diameter is disseminated through the rock.

Petrogenesis. - The marble was originally a dolomite which was metamorphosed by regional or contact metamorphism. In the later stages of the formation of the marble, differential pressure caused it to fracture. Hydrothermal solutions used these fractures as channels and soaked into the marble, dissolving some of the dolomite and leaving cavities. Later solutions, highly charged with calcium, magnesium, aluminum, silicon, carbonate, and iron ions, deposited chlorite in veinlets between the dolomite grains, particularly in the vicinity of the large fractures through the rock. Differential pressure broke these chlorite veinlets, and dolomite recrystallized in the breaks and in the cavities. Finally, the fractures which acted as channels for hydrothermal fluids became filled with chlorite.

Relative Ages of the Rock Types in the Smith Well

It is difficult to ascertain definite relative ages of rocks in the well because the exact genesis of the granite gneiss cannot be determined. If the granite gneiss is a granitic rock that has been metamorphosed or a granitic rock with primary

Figure 37. - Photomicrograph showing oligoclase in the granitic gneiss of the Smith well. The light gray and white grains in the center of the right edge are quartz. (Crossed nicols, X 32)

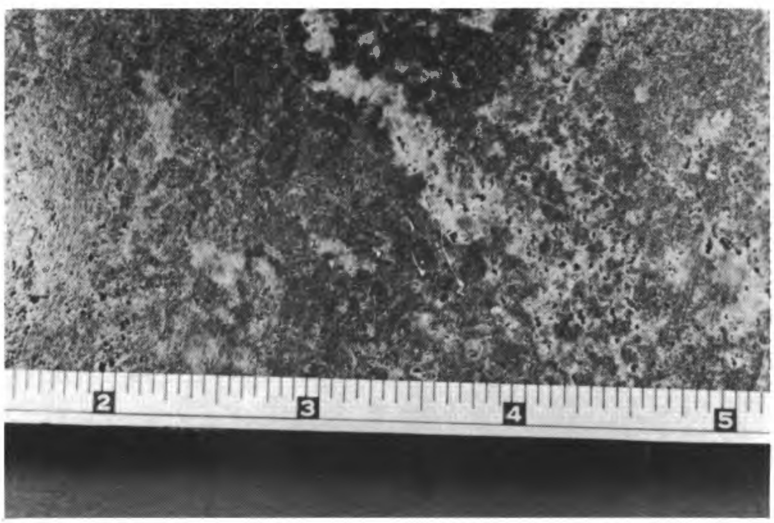

Figure 38. - Photograph of marble from the Smith well showing chlorite veinlets.

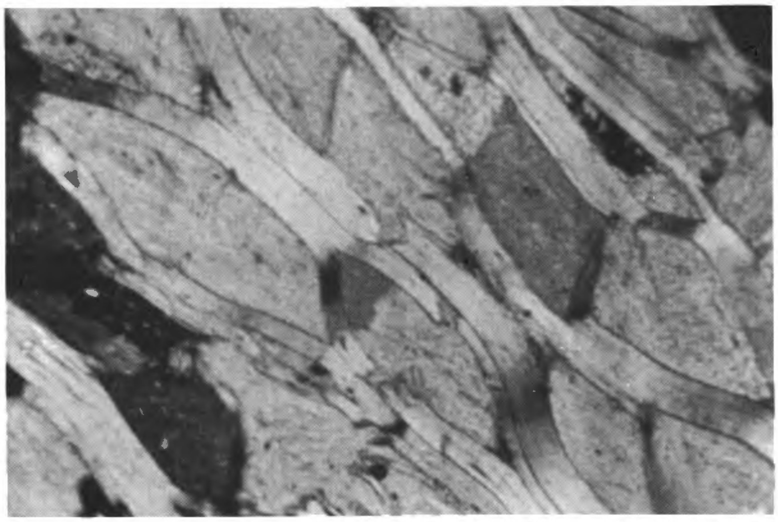

Figure 39. - Photomicrograph of marble from the Smith well showing bifurcating chlorite veinlets. Note that the veinlets in the center of the photomicrograph have been pulled apart and dolomite has recrystallized in the breaks. The two ends of the breaks match exactly. (Crossed nicols, X 32)

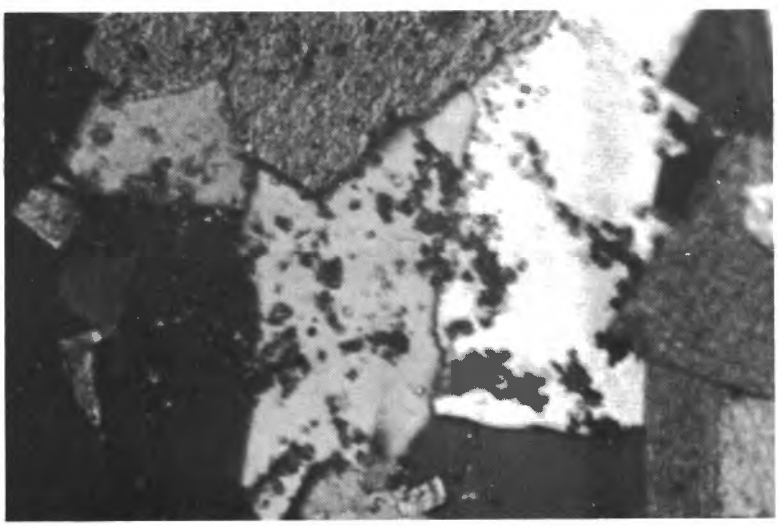

Figure 40. - Photomicrograph of marble from the Smith well showing many small scheelite crystals in a large quartz grain in the center of the photomicrograph. (Crossed nicols, X 150)

flow structure, it is younger than the dolomite and has been intruded into it. However, if the granitic gneiss is a granitized or metamorphosed sediment, the original sediment could be both older and younger than the dolomite since it both overlies and underlies the marble.

JOHNS WELL

The Johns well in McArthur Township of Logan County (fig. 1 and table 1) was drilled 106 feet into Precambrian rhyolite. Well core was recovered from the interval 3299-3308 feet, and samples were obtained from the interval 3255-3361 feet.

Rhyolite

Megascopic description. - The rhyolite is dark salmon-red, dense, aphanitic, and contains small phenocrysts of plagioclase and what appears to be bleached and altered biotite (fig. 41). Many of the feldspar phenocrysts are partially or completely altered to chlorite and serpentine. The red coloring in the rhyolite is not evenly distributed but is concentrated in streaks which delineate a flow banding. Greenish-black veins containing much chlorite and serpentine cut the rhyolite. The veins contain unreplaced quartz and phenocrysts of salmon-red plagioclase.

Microscopic description. - Two thin sections were cut from the rhyolite core, and four heavy mineral separations were made on samples from the following composite intervals: 3260-3275, 3275-3300, 3300-3335, and 3335-3361 feet. The rhyolite contains 4 to 9 percent phenocrysts of albite and biotite and a trace of pyrite and apatite, in a groundmass which contains orthoclase, quartz, and hematite and comprises 88 to 95 percent of the rock (fig. 42 and table 5). Quartz in the groundmass is as much as 0.08 mm in diameter, and orthoclase is as much as 0.12 mm. The hematite is concentrated in bands which delineate flow structure in the rhyolite. The phenocrysts of albite, much altered to chlorite, calcite, and hematite, occur as laths that range from 0.05 to 2.15 mm in length and exhibit albite and Carlsbad twins. Biotite occurs as phenocrysts that range from 0.552 to 1.45 mm in length and have altered in part to leucoxene. The leucoxene forms skeletal crystals in the centers of the biotite plates. Veins that are as much as 2 mm in width and contain a very fine grained mass of antigorite, chlorite, and unreplaced quartz and phenocrysts of albite, cut the rock. Veinlets of sericite cut both rhyolite and chlorite-rich veins.

Petrogenesis. - Flow structure, shown by a concentration of hematite particles in streaks through the rock, is an indication that the rhyolite is a flow rock. The particles of hematite originally might have been magnetite which later was oxidized. The rhyolite was cut by veins of material deficient in iron and rich in quartz and calcic feldspar which has since altered to antigorite. Hydrothermal solutions altered much of the feldspar to chlorite, antigorite, calcite, and sericite, and distributed the sericite through the rock in small veinlets. Biotite was altered to chlorite and leucoxene.

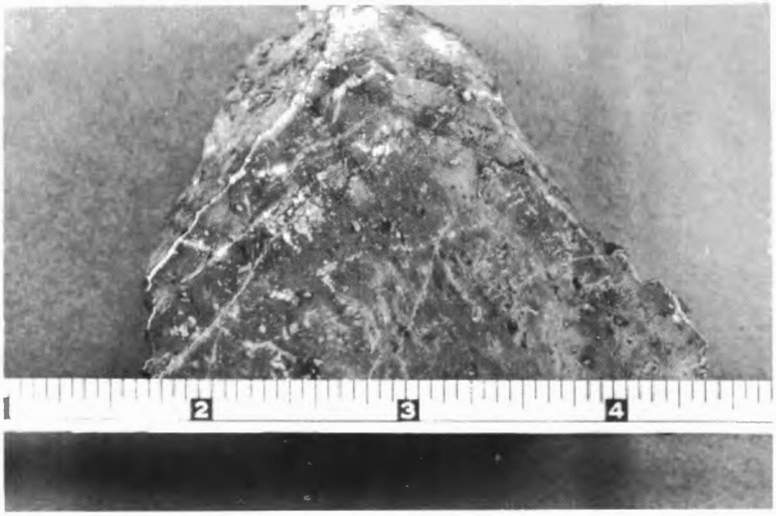

Figure 41. - Photograph of rhyolite from the Johns well.

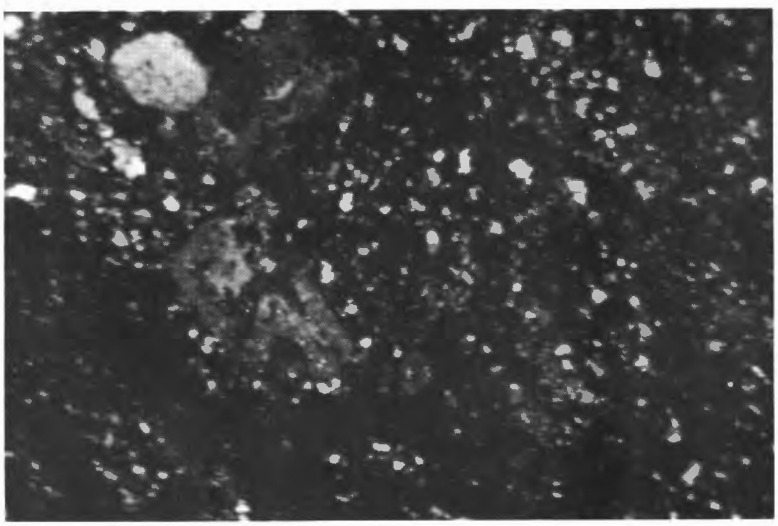

Figure 42. - Photomicrograph of rhyolite from the Johns well. A highly altered grain of albite is in the center of the left half of the view. The remainder of the view is a mass of minute grains of orthoclase, quartz, and hematite. The small white grains scattered throughout are mostly quartz. (Crossed nicols, X 32)

TABLE 5. - PERCENTAGES OF MINERALS IN THE RHYOLITE CORE OF THE JOHNS WELL

Minerals	Depth (in feet) 3299-3308
Groundmass	88-93
(Quartz)	
(Orthoclase)	
(Hematite)	
Pyrite	0.02-0.03
Leucoxene	0.1-1
Apatite	0-tr.
Rutile	0-tr.
Albite	4-7
Enstatite	0-tr.
Augite	0-0.1
Hornblende	0-tr.
Tourmaline	0-tr.
Zircon	tr.-2
Muscovite	tr.-2
Chlorite	0-1
Antigorite	0-1

ADAMS WELL

The Adams well in Wayne Township of Clinton County (fig. 1 and table 1) was drilled 67 feet into Precambrian diorite. Well cuttings were recovered for each 5-foot interval, and heavy mineral separations were run on samples from the intervals 3390-3425 and 3425-3457 feet. The samples were highly contaminated with shale and calcite from overlying Cambrian formations. The shale was all crushed and passed off in the fines when the samples were sieved.

Diorite cuttings are present in the well samples from the interval 3390-3457 feet and are like those in the Long well, only more highly altered. The diorite is medium grained, dark, and contains 30-63 percent andesine, 6-13 percent epidote, 2-5 percent hematite, 6-10 percent magnetite, a trace to 3 percent chlorite, and less than 1 percent each of hornblende, biotite, and leucoxene (table 6). Hematite concentration is as high as 5 percent from the interval 3390-3425 feet, and in the interval 3425-3457 feet the epidote concentration is as high as 13 percent. Plagioclase, pyroxene, and amphibole have altered in part or completely to epidote and chlorite; hematite probably formed by alteration of sulfide minerals or magnetite in the diorite.

TABLE 6. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE ADAMS WELL

Minerals	Depths (in feet)		
	3390-3425	3425-3457	3425-3457[1]
Pyrite	tr.	0	0
Hematite	5	2.85	5.2
Ilmenite	tr.	0	0
Leucoxene	tr.	tr.	tr.
Magnetite	10	6	10.9
Calcite	7.7	45	0
Orthoclase	2.7	0	0
Andesine	63.5	30	54.6
Enstatite	0	tr.	tr.
Pigeonite	tr.	0	0
Augite	0	0.38	0.69
Tremolite	tr.	tr.	tr.
Hornblende	0.74	0.54	0.91
Tourmaline	tr.	tr.	tr.
Epidote	6	13.3	24.3
Biotite	0.26	0.95	1.7
Chlorite	3	0.95	1.7

1. Recalculated, omitting contaminating minerals.

McVEY WELL

The McVey well in Wayne Township of Clinton County (fig. 1 and table 1) was drilled 2 feet into Precambrian amphibolite, which was present in the well cuttings from the interval 3463-3465 feet. The samples were badly contaminated with shale and limestone fragments, but the few fragments found consisted of about 50 percent hornblende and 50 percent plagioclase, somewhat altered. These samples looked very similar to those found in the Van Pelt well.

VAN PELT WELL

The Van Pelt well in Wayne Township of Clinton County (fig. 1 and table 1) was drilled 49 feet into Precambrian amphibolite, and cuttings were recovered for each 5-foot interval from the zone 3210-3259 feet. The amphibolite is medium grained, dark, and contains about 40-50 percent hornblende and 50-60 percent plagioclase feldspar with accessory hematite and chlorite. Lithic fragments exhibit excellent banding.

SAYLER WELL

The Sayler well in Florence Township of Erie County (fig. 1 and table 1) was drilled 24 feet into Precambrian granite gneiss. Samples were recovered for each 3-foot interval from the zone 4400-4424 feet. From the interval 4400-

4409 feet, orthoclase, quartz, and biotite are the predominant minerals with a lesser amount of plagioclase, and from the interval 4409-4424 feet, biotite and plagioclase are the predominant minerals with very little orthoclase.

WILSON WELL

The Wilson well in Concord Township of Fayette County (fig. 1 and table 1) was drilled 150 feet into Precambrian rock. Well cuttings were recovered from each 5-foot interval, and heavy mineral separations were run on samples from the following intervals: 3340-3355, 3355-3400, 3400-3435, 3435-3450, 3450-3460, and 3460-3490 feet. Two rock types, amphibolite and granite pegmatite, were identified in the Wilson well.

Amphibolite

The Wilson well is located in the same gravity anomaly as the Hopkins well, which is described in detail in this report (p. 6). The similarity of the rock chips in this well to the rock chips in the upper part of the Hopkins well leads the writer to consider them to be amphibolite like that in the Hopkins well. Amphibolite chips from the Wilson well do not show a foliation and neither do those from the Hopkins well, although thin sections of the same rock in the Hopkins well do show an obscure foliation. The amphibolite in the cuttings from the Wilson well is medium grained, dark, and occurs as large lithic fragments composed of 37-49.2 percent labradorite, 18-40 percent hornblende, 2-12 percent hypersthene, a trace to 8 percent biotite, 1-2 percent pigeonite, as much as 2 percent garnet, 1 percent magnetite, and traces of chlorite, hematite, sphene, and zircon (table 7). The concentration of the various minerals varies with depth in the well, as shown by examination of cuttings under the binocular microscope. Labradorite makes up as much as 90 percent of the rock in certain intervals, hypersthene predominates in other intervals, and in yet other intervals hornblende and labradorite are in about equal abundance. Labradorite is very little altered and occurs in laths which are as much as 8 mm long and exhibit moderate albite twinning. Hypersthene occurs in elongate grains as much as 6 mm in length and exhibits moderate to strong pleochroism from pink to light apple green. Hornblende in this rock exhibits pleochroism from dark green to light brown. Biotite, hornblende, labradorite, pigeonite, and garnet are attached in lithic fragments; red garnet is notably concentrated in the zone 3450-3460 feet.

Granite Pegmatite

Two small lithic fragments of salmon-red microcline and white oligoclase were found in the interval 3375-3385 feet; several of these were found in the interval 3340-3355 feet. The mineral separation of the interval 3340-3355 feet contains 27 percent quartz, 18 percent orthoclase, a trace of zircon and rutile, and 45 percent labradorite, with small amounts of hypersthene, hornblende, pigeonite, and biotite (table 7). The quartz, orthoclase, zircon, and rutile are probably from a granite pegmatite; however, the percentages are not reliable indications of the amount of pegmatite present in the well because the crystalline rocks are immediately overlain by orthoclase-rich arkosic sandstone which has contaminated this sample.

TABLE 7. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE WILSON WELL

Minerals	Depths (in feet)					
	3340-3355	3355-3400	3400-3435	3435-3450	3450-3460	3460-3490
Quartz	27	1	tr.	8.7	tr.	tr.
Hematite	tr.	--	--	tr.	tr.	tr.
Leucoxene	tr.	--	--	--	--	--
Rutile	tr.	--	--	--	--	--
Magnetite	1	1	0.5	0.05	1	1
Calcite	--	tr.	tr.	tr.	tr.	tr.
Orthoclase	18	--	--	--	--	--
Oligoclase	--	tr.	4.3	2.9	25	5.2
Labradorite	45	48	49.2	46.4	37	46.8
Hypersthene	4.5	4	3.64	12.45	1.9	4.7
Pigeonite	0.2	1	0.9	2.08	tr.	4
Hornblende	4.1	40	38.67	18.67	30.4	37.6
Garnet	--	--	--	--	1.9	--
Zircon	0.2	--	--	tr.	--	--
Sphene	--	--	--	--	tr.	--
Biotite	tr.	5	2.27	8.3	3.8	2.35
Chlorite	--	--	--	tr.	--	--

Relative Ages of the Rocks in the Wilson Well

The similarity of rock fragments in this well to those in the Hopkins well, and the location of both wells in the same gravity anomaly, leads the writer to infer the same genesis for the rocks in both wells. Very possibly the amphibolite was originally an intrusive basalt or gabbro which became metamorphosed and was intruded by granitic material. The pegmatite could have been formed in the amphibolite during the late stages of the cooling of the granitic intrusive.

BARNES WELL

The Barnes well in Jasper Township of Fayette County (fig. 1 and table 1) was drilled 30 feet into Precambrian trachyte porphyry. Cuttings were obtained for each 10-foot interval from the zone 3380-3410 feet, and one composite heavy mineral separation was made on the interval 3380-3410 feet.

The Precambrian trachyte porphyry contains 91 percent groundmass made up of potassium feldspar with much very fine grained hematite (table 8). Eight percent of the rock is made up of andesine phenocrysts as much as 0.4 mm in diameter, most of which have altered completely or in part to serpentine. Some of the rock chips contain 2 or 3 percent small grains of chalcopyrite, though this mineral does not appear in the mineral separations. Less than 1 percent each of hornblende, magnetite, spinel, epidote, and enstatite are present in the separation. Hornblende is pleochroic in shades of green and yellow-brown and occurs, as does enstatite, in grains as much as 0.2 mm in length. The spinel is isotropic and brilliant green in plain light.

TABLE 8. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE BARNES WELL

Minerals	Depth (in feet) 3380-3410
Groundmass (Mostly K Feldspar)	91.36
Magnetite	0.07
Andesine	7.94
Enstatite	0.03
Hornblende	0.56
Epidote	tr.
Spinel	0.04

MARSHALL WELL

The Marshall well in Adams Township of Guernsey County (fig. 1 and table 1) is of great interest for several reasons. It is the deepest well drilled in Ohio to date, having a total depth of 8602 feet; it penetrates 277 feet of Precambrian granite gneiss and amphibolite; and it is the first well to be drilled into the Precambrian in the southeastern part of the State.

Granite Gneiss

Granite gneiss is present in the well cuttings from the interval 8325-8335 feet. It is medium grained and contains principally orthoclase and quartz with lesser amounts of plagioclase, biotite, and hornblende. The lithic fragments of the rock show a gneissoid texture.

Amphibolite

Amphibolite is present in the well samples from the interval 8335-8602 feet. It is medium grained and contains about 45-50 percent hornblende and 50-55 percent plagioclase feldspar with some accessory olivine, garnet, and chlorite. Foliation of the amphibolite is indicated by some small lithic fragments and by the many platy pieces of plagioclase.

ARTING WELL

The Arting well in Peru Township of Huron County (fig. 1 and table 1) was drilled 350 feet into Precambrian rock, but a complete set of samples for the depth penetrated was not kept. Samples were kept for the following intervals: 3800-3920, 3925-3929, 3977-3980, 4001-4003, 4093-4100, and 4130-4150 feet, in 4-foot composite intervals. The samples from this well look much like those from the Vance well described by Lamey (Stout and Lamey, 1940). Two rock types, granite gneiss and biotite schist, are present.

Granite Gneiss

Samples from the intervals 3800-3917, 4093-4100, and 4130-4150 feet contain predominantly salmon-pink potassium feldspar with a smaller amount of white albite, colorless transluscent quartz, and plates of biotite. The biotite, potassium feldspar, and quartz are present in grains as much as 3 mm in diameter and occur as individual grains rather than as lithic fragments, indicating that the rock is at least moderately coarse grained. If the rock were fine grained, lithic fragments containing two or more of the minerals of the rock should occur in the cuttings rather than large monomineralic grains.

Biotite Schist

Samples from the intervals 3917-3920, 3925-3929, 3977-3980, and 4001-4003 feet contain predominantly colorless transluscent quartz, biotite plates as much as 2 mm in diameter, and a small amount of transluscent white plagioclase exhibiting well developed twinning. The large amount of biotite in large plates indicates that the rock is schistose rather than gneissic.

Relative Ages of the Rocks in the Arting Well

The biotite schist was probably originally a Precambrian pelitic sediment which was intruded by granitic material. After the intrusion, the entire area was subjected to regional stresses which metamorphosed both rocks, much as in the Vance well (Stout and Lamey, 1940) in Delaware County. It is also possible that the granitic material was injected syntectonically during regional metamorphism.

BORNE WELL

The Borne well in Henrietta Township of Lorain County (fig. 1 and table 1) penetrated 20 feet of Precambrian granite gneiss from which cuttings were recovered for each 5-foot interval from the zone 4570-4590 feet. The granite gneiss is medium grained and has a somewhat varied mineral content in different intervals. From 4570-4577 feet, orthoclase, quartz, and biotite are all equally abundant; from 4577-4583 feet, orthoclase, biotite, quartz, and plagioclase were noted; from 4583-4587 feet, biotite and quartz are present with much orthoclase; and from 4587-4590 feet, biotite and quartz are the predominant minerals with a very small amount of orthoclase. Both the platiness of the quartz grains and the concentration of minerals in zones indicate the rock is a granite gneiss rather than merely a granite.

WARNER WELL

The Warner well in Granger Township of Medina County (fig. 1 and table 1) was drilled 88 feet into Precambrian granite gneiss. Samples were obtained for each 10-foot interval from the depth 6640-6720 feet, but no heavy mineral separation was made on the samples.

Two predominant types of lithic fragments are present in the samples of granite gneiss. One type contains about 40 percent salmon-pink microcline as much as 5. 2 mm in diameter, white albite that shows good cleavage in grains as much as 6 mm in diameter, colorless transluscent quartz that shows very good conchoidal fracture in grains as much as 5. 2 mm in diameter, and muscovite in thin books of plates as much as 5. 8 mm in diameter. Albite composes about 20 percent, microcline about 40 percent, and quartz and muscovite the other one-third of the fragments. The second type of lithic fragment contains biotite in thin books of plates as much as 3 mm in diameter enclosed in colorless transluscent quartz grains as much as 6. 5 mm in diameter but more generally averaging 4 mm. The books of biotite are all alined parallel to each other and define a definite foliation in the rock. The percentage of quartz and biotite in these fragments is about equal. It appears that this rock is a granite gneiss with alternating foliae of feldspar-muscovite-quartz and quartz-biotite.

WALKER WELL

The Walker well in Lost Creek Township of Miami County (fig. 1 and table 1) was drilled 245 feet into Precambrian trachyte-latite porphyry. Samples were obtained for each composite 5-foot interval from the zone 3255-3500 feet, and heavy mineral separations were made on samples from the following intervals: 3255-3280, 3280-3310, 3310-3335, 3335-3380, 3380-3415, 3415-3435, 3435-3460, and 3460-3500 feet.

The trachyte-latite porphyry is composed of 2-78 percent aphanitic groundmass which is practically all potassium feldspar and the alteration products chlorite and sericite (table 9). Phenocrysts of oligoclase comprise 17-98 percent of the rock and occur in laths as much as 2 mm long; the concentration of these phenocrysts varies with depth in the well. Magnetite ranges from 1-13 percent and occurs in grains as much as 0. 05 mm in diameter; the highest percentage is in the interval 3415-3435 feet. Less than 1 percent each or pyrite, hematite, leucoxene, hypersthene, hornblende, garnet, zircon, chlorite, biotite, pigeonite, and epidote were identified in the heavy mineral separations. White calcite, in grains as much as 33 mm in diameter, was observed under the binocular microscope, although it does not appear in the mineral separations. Probably the calcite is soft enough that it was crushed in grinding the rock chips for the separations and was lost in the fine material. Most of these calcite grains are in lithic fragments with an aphanitic groundmass and have a rim of chlorite at the contact of the calcite and the groundmass. The calcite and chlorite probably were formed in late veins.

TABLE 9. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE WALKER WELL

Minerals	Depth (in feet)							
	3255-3280	3280-3310	3310-3335	3335-3380	3380-3415	3415-3435	3435-3460	3460-3500
Pyrite	0.025	0.04	0.04	0.02	tr.	tr.	tr.	tr.
Quartz	4.7	--	--	--	--	tr.	--	tr.
Hematite	0.015	0.015	0.03	0.04	--	tr.	0.03	0.036
Limonite	--	--	--	--	--	--	tr.	--
Leucoxene	0.8	0.34	0.59	0.64	0.27	0.15	1.3	0.96
Magnetite	7	9	3	9	1	13	1	1
Altered groundmass (K Feldspar)	9.2	4.5	2	72.4	78.8	52	58.5	19.6
Oligoclase	78.5	86.1	98	17.3	19.9	34.9	39.2	78.8
Hypersthene	0.015	0.005	--	tr.	0.015	tr.	tr.	0.18
Pigeonite	--	--	--	tr.	--	tr.	--	tr.
Hornblende	0.015	tr.	0.03	tr.	0.015	--	--	tr.
Zircon	0.015	tr.	tr.	--	tr.	--	tr.	--
Garnet	0.015	--	tr.	--	--	--	--	--
Epidote	--	--	--	--	--	0.15	--	0.24
Biotite	--	--	0.01	--	--	--	--	tr.
Chlorite	--	--	tr.	--	--	--	--	--

LEVERING WELL

The Levering well in Washington Township of Miami County (fig. 1 and table 1) was drilled 129 feet into Precambrian granite. Samples were obtained from the zone 3282-3411 feet in intervals of 4 to 10 feet (table 10), and mineral separations were prepared on samples from the composite intervals 3282-3332 and 3332-3411 feet.

The granite samples are composed of 69-74 percent microcline, 24-29 percent quartz, 1-2 percent magnetite, and very small amounts of zircon, hornblende, biotite, tourmaline, augite, garnet, hematite, and leucoxene. The microcline is salmon-pink, generally exhibits good grid twinning under the polarizing microscope, and is the major mineral in lithic fragments which in addition to microcline contain quartz and accessory minerals. Most of the quartz is in colorless individual grains, although some is in lithic fragments with microcline and accessory minerals.

TABLE 10. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE LEVERING WELL

Minerals	Depth (in feet) 3282-3411
Quartz	29
Hematite	0.01
Leucoxene	0.04
Magnetite	2
Microcline	69
Pigeonite	0.01
Hornblende	0.02
Zircon	0.04
Garnet	tr.
Tourmaline	0.02
Biotite	0.01

LONG WELL

The Long well in Monroe Township of Pickaway County (fig. 1 and table 1) was drilled 110 feet into Precambrian rock. Well samples were recovered from each 5-foot interval, and heavy mineral separations were run on samples from the following intervals: 3180-3190, 3190-3215, 3215-3235, and 3235-3255 feet (table 11). This well is in the same gravity anomaly as the Hopkins well and contains similar rocks. Three rock types were identified in this well: marble, biotite gneiss, and gabbro.

Marble

Marble is present in the interval 3145-3180 feet. It is medium grained and contains 90-95 percent white dolomite which occurs in grains as much as 0.05

TABLE 11. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE LONG WELL

Minerals	Depths (in feet)			
	3180-3190	3190-3215	3215-3235	3235-3255
Pyrite	tr.	tr.	--	tr.
Quartz	--	tr.	tr.	--
Hematite	2	tr.	tr.	tr.
Limonite	tr.	tr.	tr.	--
Leucoxene	--	--	tr.	--
Magnetite	1	3	12	7
Calcite	--	1	tr.	1
Oligoclase	28	3	4	2
Labradorite	64	54	68	81
Hypersthene	3. 5	35	12	6. 3
Augite	1. 3	3	2	1
Hornblende	--	--	2	1
Zircon	0. 1	--	tr.	--
Garnet	2	--	--	--
Biotite	--	tr.	tr.	0. 7
Chlorite	--	--	--	tr.

mm in diameter, 3-4 percent garnet and diopside, and a trace of pyrrhotite and chalcopyrite. A heavy mineral separation was not run on the marble.

Biotite Gneiss

Chips of biotite gneiss are present in small quantities in all samples below 3180 feet but are not present above this depth. The fragments are foliated and are composed of very small grains of oligoclase with thin bands of biotite plates. In the light fraction of the mineral separations, oligoclase comprises 2-28 percent of any given interval; the interval 3180-3190 feet contains the highest percentage of oligoclase, which indicates more biotite gneiss in this part of the well. In the mineral separations, biotite is present only as flakes attached to oligoclase.

Gabbro

Gabbro occurs in the interval 3180-3255 feet and comprises the greatest percentage of the well samples. The gabbro is equigranular, fine grained, and contains 54-81 percent labradorite, 3. 5-35 percent hypersthene, 1-12 percent magnetite, 1-3 percent augite, 1-2 percent hornblende, and traces of chlorite, biotite, and pyrite (table 11). These minerals occur together in large lithic fragments, those of which in the interval 3180-3190 feet are heavily stained with hematite. The labradorite as seen under the binocular microscope occurs as transluscent laths that show well-developed albite twinning and are as much as 0. 06 mm in length, and is concentrated more at some intervals than at others. Grains of hypersthene occur as elongate grains as much as 0. 06 mm in length and in the heavy fraction of the separation exhibit moderate to strong pleochroism from pink to light green.

Relative Ages of the Rocks in the Long Well

The marble and probably the biotite gneiss were sedimentary rocks that were regionally metamorphosed. The gabbro most likely was intruded after the metamorphism of these sedimentary rocks. It is possible that the gabbro is a metamorphic rock such as a pyroxene hornfels; however, the high plagioclase content indicates that this rock is more likely of igneous origin. If the rock were a pyroxene hornfels, it would most likely have been intruded into the sedimentary rocks as a gabbro or basalt and then later metamorphosed along with the sediments around it.

BARLAGE WELL

The Barlage well in Liberty Township of Putnam County (fig. 1 and table 1) was drilled 27 feet into Precambrian granite, and cuttings were obtained from the interval 3250-3377 feet (table 12). Abundant angular salmon-pink orthoclase and transluscent quartz grains, with minor amounts of white plagioclase and heavy accessory minerals, were observed under the binocular microscope. Most of the heavy accessory minerals occur in lithic fragments with feldspar. Some quartz is also in lithic fragments with feldspar but most of it occurs as individual grains. Due to scarcity of samples, only one aggregate sample for the 3250-3377-foot interval was prepared for separation. The heavy and light fractions of the separation contain 64 percent orthoclase, 29 percent quartz, 5 percent oligoclase, 1.4 percent magnetite; small amounts of pyrite, hematite, leucoxene, hornblende, and zircon; and a trace of hypersthene, garnet, and tourmaline.

TABLE 12. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE BARLAGE WELL

Minerals	Depth (in feet) 3250-3377
Pyrite	0.02
Quartz	29
Hematite	0.04
Leucoxene	0.03
Magnetite	2.4
Orthoclase	63.7
Oligoclase	3.8
Hornblende	0.01
Zircon	0.01
Garnet	tr.
Tourmaline	tr.
Biotite	tr.

WATSON WELL

The Watson well in Pleasant Township of Seneca County (fig. 1 and table 1), the second well drilled into the Precambrian in Ohio, reached a total depth of 2935 feet. It was started by the Sun Oil Company on January 26, 1912, but no samples, completion date, or log of the well below the Green break in the Trenton were kept. Mr. G. W. Myrs of the Sun Oil Company is sure granite was reached at about 2900 feet, from the drillers' description. (Notation on partial log of well on file with the Ohio Division of Geological Survey).

HETRICK WELL

The Hetrick well in Rice Township of Sandusky County (fig. 1 and table 1) was drilled to a depth of 2796 feet and passed into what the driller termed "granite wash" at 2701 feet. No rock samples were kept, and the only record of the well is a very generalized driller's log on file with the Ohio Division of Geological Survey. The Bruns well immediately north of this well passed into granite at 2667 feet, so it seems most likely that what the driller here termed granite wash is granite or granite gneiss.

BRUNS WELL

The Bruns well in Woodville Township of Sandusky County (fig. 1 and table 1) was drilled 155 feet into Precambrian rock. Samples were obtained for each 5-foot interval from a depth of 2667-2822 feet, and heavy mineral separations were run on samples from the following composite intervals: 2667-2712, 2712-2762, 2762-2797, and 2797-2822 feet. Granite and amphibolite are present in this well.

Granite

Granite is present in the intervals 2667-2762 and 2797-2822 feet. It contains 65-86 percent microcline, 0-9.5 percent oligoclase, 9-27 percent quartz, 3-6 percent hornblende, and small amounts of zircon, biotite, and garnet (table 13). Minerals in this rock are very rarely present in lithic fragments, but rather are present as monomineralic grains, which indicates that the rock probably is coarse grained. The microcline, under the binocular microscope, is pink and occurs in grains as much as 0.6 mm in diameter, and under the petrographic microscope it shows excellent grid twinning. Quartz occurs as grains that are as much as 0.6 mm in diameter and show undulatory extinction under the polarizing microscope. Biotite occurs in thin books as much as 0.8 mm in diameter.

Amphibolite

Amphibolite is present in the interval 2762-2797 feet. It contains 62.3 percent oligoclase, 27 percent hornblende, and 3 percent biotite (table 13). The oligoclase is transluscent, as much as 0.6 mm in diameter, and occurs in lithic fragments with hornblende and biotite. Hornblende has good prismatic cleavage, occurs in grains as much as 1.2 mm in length, and is pleochroic from very dark green to medium yellow-green. When the grains are oriented so that the Z optic direction is perpendicular to the stage of the microscope, light is transmitted only on the thin edges of the grains, which appear dark green. Although no alinement of hornblende laths was noted in the samples, the mineralogic characteristics and similar appearance of fragments in this well to those of the amphibolite in the Hopkins well lead the writer to infer that these are also fragments of an amphibolite rather than of an igneous rock such as a diorite.

Relative Ages of the Rocks in the Bruns Well

The amphibolite probably was a preexisting andesite or diorite that was intruded by a granite during or after a period of regional metamorphism.

TABLE 13. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE BRUNS WELL

Minerals	Depths (in feet)			
	2667-2712	2712-2762	2762-2797	2797-2822
Quartz	9.7	14	3.5	27.8
Microcline	86.6	70	3.5	65
Oligoclase	--	9.5	62.3	--
Hornblende	3.7	5.2	27	6.3
Zircon	tr.	1.3	0.7	0.7
Garnet	--	tr.	--	--
Biotite	--	0.33	4	0.2

HAFF WELL

The Haff well in Townsend Township of Sandusky County (fig. 1 and table 1) was drilled 33 feet into Precambrian granite, which was present in the well cuttings in the interval 3090-3123 feet. It is medium grained and contains predominantly pink orthoclase and quartz with accessory biotite and plagioclase.

NELSON WELL

The Nelson well in Perry Township of Shelby County (fig. 1 and table 1) was drilled 125 feet into Precambrian trachyte porphyry, and samples were recovered in 3-6-foot intervals from the zone 3140-3265 feet. Mineral separations were prepared on samples from the composite intervals 3140-3160, 3160-3200, 3200-3235, and 3235-3265 feet.

The trachyte is very fine grained, porphyritic, and possibly gneissoid. It is composed of 48-72 percent orthoclase, 20-48 percent andesine, trace to 9 percent quartz, trace to 6 percent magnetite, and small amounts of biotite, hornblende, hypersthene, garnet, ilmenite, rutile, hematite, leucoxene, zircon, tourmaline, pigeonite, apatite, calcite, and chlorite (table 14). The fragments are composed

TABLE 14. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE NELSON WELL

Minerals	Depths (in feet)			
	3140-3160	3160-3200	3200-3235	3235-3265
Quartz	9	5	--	4.6
Hematite	tr.	tr.	1.6	--
Ilmenite	tr.	tr.	0.2	tr.
Leucoxene	tr.	tr.	0.10	tr.
Rutile	--	--	tr.	--
Apatite	tr.	tr.	--	--
Magnetite	tr.	1	2	6
Calcite	--	--	tr.	--
Orthoclase	68	72	48	68
Andesine	22	22	48	20.4
Hypersthene	tr.	tr.	1.6	0.8
Pigeonite	--	tr.	tr.	0.03
Hornblende	tr.	tr.	0.06	0.15
Zircon	tr.	tr.	--	0.02
Garnet	tr.	--	--	tr.
Tourmaline	--	--	--	tr.
Biotite	--	--	tr.	tr.
Chlorite	--	--	0.04	--

of tablet-shaped phenocrysts of salmon-pink orthoclase, which exhibit good Carlsbad twins and are as much as 0.08 mm in diameter, in a matrix of small andesine and magnetite grains which range up to 0.02 mm in diameter. The andesine in the matrix is white and generally much sausseritized. Calcite, chlorite, and magnetite are found in all samples in lithic fragments. The calcite and chlorite are much softer than the feldspars, and during the process of crushing and sieving the samples, practically all the calcite and chlorite was pulverized and discarded in the fines. As a result, calcite and chlorite do not appear in mounted slides of the mineral separations. The calcite is white and ranges up to 0.12 mm in diameter, and the chlorite is green and occurs in rosettes as much as 0.06 mm in diameter. Magnetite is in masses of very small grains associated with calcite and chlorite. It appears that two types of magnetite, magmatic and post magmatic, are present in the samples. Magnetite found in association with orthoclase and andesine in lithic fragments of syenite probably was formed at the time the rock crystallized, but the magnetite associated with calcite and chlorite seems to have entered the rock in hydrothermal emanations of the cooling granitic intrusive and formed late veins.

FOGT WELL

The Fogt well in Salem Township of Shelby County (fig. 1 and table 1) was drilled 73 feet into Precambrian rhyolite, and samples were recovered from each 5-foot interval. Heavy mineral separations were run from the intervals 3287-3326 and 3326-3360 feet. The rock is composed of 81-94 percent aphanitic groundmass, 1-3 percent magnetite, and less than 1 percent each of chlorite, apatite, zircon, garnet, hornblende, pyrite, leucoxene, hypersthene, hematite, and biotite (table 15). The groundmass is about 40-47 percent altered microcline and 6-19 percent

TABLE 15. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE FOGT WELL

Minerals	Depths (in feet)	
	3287-3326	3326-3360
Pyrite	--	0.03
Quartz	6	19
Hematite	0.05	--
Leucoxene	0.35	0.30
Magnetite	1	3
Apatite	--	0.15
Groundmass[1]	94	81
(Microcline)	47	40.5
Hypersthene	--	0.07
Pigeonite	0.75	--
Hornblende	--	tr.
Zircon	--	0.35
Garnet	tr.	tr.
Biotite	--	0.025
Chlorite	tr.	0.1

1. Percentage of groundmass includes percentage of microcline.

quartz. Well chips, as seen under the binocular microscope, are composed of aphanitic groundmass containing small euhedral magnetite grains. Unaltered fragments of groundmass are dark red, but most fragments are highly sausseritized. The groundmass is cut by innumerable small dolomite veins bordered with hematite. Emplacement of the late dolomite veins and the alteration of the groundmass materials most likely resulted from effects of late hydrothermal fluids and gasses.

KILLIAN WELL

The Killian well in Liberty Township of Wood County (fig. 1 and table 1) was drilled 43 feet into Precambrian granitic gneiss. Well cuttings were obtained for 4- or 5-foot intervals from the zone 2884-2927 feet. The 2899-2980- and 2922-2927-foot intervals contain much salmon-pink potassium feldspar as much as 0.5

mm in diameter, a smaller amount of colorless transluscent quartz showing good conchoidal fracture, and about 15 percent biotite in plates as much as 1 mm in diameter. The intervals 2884-2899 and 2908-2922 feet contain predominantly colorless transluscent quartz and much biotite in plates as much as 1 mm in diameter; potassium feldspar makes up less than 10 percent of these intervals. The rock is thought to be gneiss because of the relatively high percentage of biotite plates and the alternation of quartz-biotite and quartz-biotite-feldspar zones. Practically all the minerals occur as individual fragments, which indicates that the rock is at least moderately coarse grained. If the rock were fine grained, the mafic minerals should appear in lithic fragments with feldspar and quartz, whereas the presence of many monomineralic fragments indicates that these fragments are of a larger grain which has been crushed in the drilling process.

NORA HECK WELL

The Nora Heck well in Crawford Township of Wyandot County (fig. 1 and table 1) was drilled approximately 7 feet into Precambrian granite. The exact depth of granite penetrated cannot be determined as the granite samples are highly contaminated with quartz and feldspar grains from overlying arkose and quartz sandstone. The sample interval 2780-2795 feet contains a few lithic fragments of angular quartz and microcline; but most of the sample in this interval is composed of rounded quartz grains that have been broken. In the interval 2795-2801 feet there are many lithic fragments of feldspar and quartz, biotite plates, and angular quartz grains; this interval appears to be granite. One mineral separation was run on the interval 2780-2801 feet. The light fraction of the separation contains 30 percent quartz, 59 percent microcline, and 10 percent albite; the heavy fraction contains small amounts of zircon, garnet, hornblende, pyrite, biotite, tourmaline, magnetite, hematite, and leucoxene, (table 16). Undoubtedly the quartz percentage

TABLE 16. - PERCENTAGES OF MINERALS IN CUTTINGS OF THE NORA HECK WELL

Minerals	Depth (in feet) 2780-2801
Pyrite	0.01
Quartz	30
Hematite	tr.
Leucoxene	tr.
Magnetite	tr.
Microcline	59
Albite	10
Hornblende	0.01
Zircon	0.36
Garnet	0.02
Tourmaline	tr.
Biotite	tr.

is high because of contamination of the sample by quartz from the overlying arkose and sandstone. Under the binocular microscope, the salmon-pink microcline and the white albite are associated in lithic fragments. Grains of microcline in the light fraction of the mineral separation show grid twinning under the polarizing microscope, and most heavy accessory minerals are seen in lithic fragments with the microcline.

PARSELL WELL

The Parsell well in Jackson Township of Wyandot County (fig. 1 and table 1) was drilled to a total depth of 5632 feet. According to the drillers it passed into granite wash at 3040 feet and bottomed in granite. No samples of the Cambrian or Precambrian rocks of the well were kept.

REEVALUATION OF ROCK TYPES PREVIOUSLY DESCRIBED IN THE LITERATURE

The writer examined the samples from the Vance, Friend, and Norris wells, all of which had been described in the literature. The interpretations of the rock types by the various authors fit fairly well the pattern of rock types developed from this study.

VANCE WELL

This well is on the outermost edge of the gravity anomaly in which are located the Hopkins, Long, Wilson, Adams, and Barnes wells. Dr. Lamey (Stout and Lamey, 1940) interpreted the rocks in this well as being a gneiss complex formed by the injection of granitic material into basic igneous rocks. This corroborates the writer's contention that this anomaly contains Precambrian sediments into which were injected basic igneous rocks such as gabbro or basalt; the whole sequence then was later regionally metamorphosed, and granitic material was injected syntectonically or post tectonically. This well, if drilled deeper, might penetrate marble and hornfels as did several wells in the area of the anomaly.

FRIEND WELL

The rocks of this well are very anomalous in comparison with those of all other wells in Ohio. The well contains more than 800 feet of black crystalline limestone in which it bottoms, and does not pass into a granitic basement. Miss Wasson (1932) described an arkose containing much weathered granodiorite in the interval 4360-4382 feet. The writer has examined these samples and believes that the rocks are not appreciably altered; they appear to be granite or granodiorite. It is possible that these samples are from a pegmatite or granitic dike that cut the black limestone. Dr. Bass (personal communication) of the Carnegie Institute in Washington believes that the limestone in this well bears the same relation to the marble and amphibolite in wells near it that the Mistassini series does to the Grenville series in Canada.

NORRIS WELL

Condit (1913) described the crystalline rock in the Norris well as granite, probably gneissoid. Since this study, wells have been drilled into the basement to the north, east, and west of this well and all have bottomed in granite. It seems, then, that in the vicinity of Findlay the Paleozoic rocks rest directly on a granitic basement.

AGE OF PRECAMBRIAN ROCKS IN OHIO

The uniformly high grade of metamorphism, geographic location, and presence of marble in practically all wells in Ohio east of a fairly sharply limited area suggests correlation of the rocks east of this line with the Grenville series. This correlation has been confirmed by Dr. Manuel Bass of the Carnegie Institute, who has determined eight ages (table 17) on the basis of rubidium-strontium con-

TABLE 17. - AGE OF PRECAMBIAN ROCKS IN SIX WELLS

(Determined by Dr. Manuel Bass, Carnegie Institute, Washington)

Well	Mineral	Rb-Sr age (millions of years)
Killian	Biotite	950
Bruns	Biotite	940
Arting	Biotite	920
Vance	Biotite	950
	Muscovite	950
Wilson	Biotite	930
Hopkins	Biotite	940
	Muscovite	980

tent of muscovite and biotite. Dr. Bass is now determining ages from potassium-argon content of more rocks in wells in Ohio and Michigan. No dates have been obtained at present for rock types in any of the wells to the west of the Grenville boundary line (personal communication).

CONCLUSIONS

The known Precambrian rocks of Ohio can be divided into two principal provinces on the basis of rock types. East of a line from Sandusky Bay to Clermont County (fig. 1) the principal rock types are marble, hornfels, and amphibolite, with accompanying granite gneiss and pegmatite. To the west of this line the principal rocks are granite, syenite, latite, trachyte, and a small amount of biotite schist. To the west of this line the Precambrian rocks are only 2,000 to 3,000 feet below the surface, whereas to the east of this line the depth to the Precambrian rapidly increases from 3600 feet in Fayette County to 8330 feet in Guernsey County. Amphibolite and marble with a high content of sulfide minerals in the region of Fayette County, east of the dividing line, probably account for the high gravity anomaly in that area. Dr. Manuel Bass of the Carnegie Institute has determined the ages of biotite and muscovite from the wells east of this line and has found that they range from 920 to 980 million years in age, which makes them equivalent in age to the Grenville series of the Precambrian. The presence of marble in most of the wells to the east of this line also is a point of similarity of these rocks to the Grenville series. The wells east of this line which contain no marble do so, most likely, because they were not drilled deep enough to penetrate the marble. One well, the Friend well, which is to the east of this line, contains 800 feet of black crystalline limestone which is highly fractured and healed with clear calcite. Dr. Bass believes that this limestone bears the same relation to the marble in the other wells east of this line that the Mistassini series does to the Grenville series in Canada (personal communication).

Some of the lavas to the west of this line show evidence of being surface flows and some seem to be shallow intrusives. Many of the lavas contain late veins of calcite and chlorite. The basal Cambrian rock in practically all wells immediately east of this line is arkose, which perhaps came from the erosion of the granites west of the line. The metamorphic rocks on both sides of the line have been subjected to regional metamorphism, with some accompanying thermal metamorphism and igneous emplacement.

The lavas west of this line are perhaps younger in age than the marble and granite, which have been dated as Grenville. If this is the case, they probably are late Precambrian or possibly early Cambrian; Dr. Bass plans to make age determinations on some of these lavas.

It is believed that to the east of the line, granite underlies the marble, amphibolite, hornfels, and schists but has not been penetrated. Pegmatites in these rocks were formed by gases and vapors emanated from the deeper granitic bodies. The writer believes that these granite bodies, as yet unpenetrated, are the same age as those to the west which have been penetrated.

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